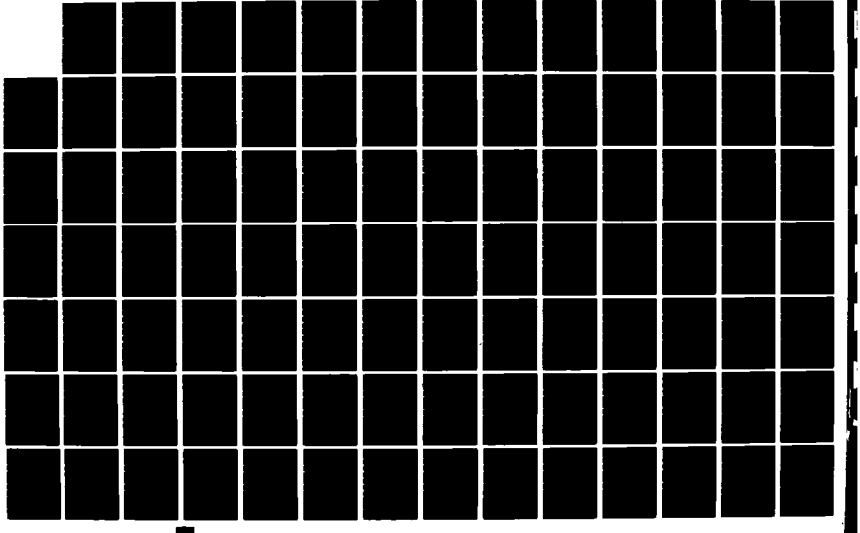
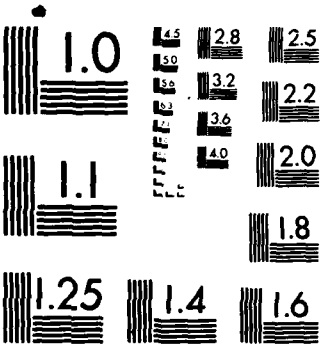
AD-A161 433 A THERMODYNAMIC SYSTEM ANALYSIS MODEL OF A DIESEL ENGINE(U) RUTGERS - THE STATE UNIV NEW BRUNSWICK N J DEPT OF MECHANICAL K T RHEE ET AL 16 OCT 85 1/2

UNCLASSIFIED ARO-21770 4-EG DAAG29-84-K-0158 F/G 21/7 NL





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AD-A161 433

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1. REPORT NUMBER: ARO 21770.4-EG	2. GOVT ACCESSION NO.: N/A	3. RECIPIENT'S CATALOG NUMBER: N/A

4. TITLE (and Subtitle)
A Thermodynamic System Analysis Model of a Diesel Engine

5. TYPE OF REPORT & PERIOD COVERED
Final Report
8/1/84 - 7/31/85

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
K. T. Rhee, X. L. Yang, and S. L. Chang

8. CONTRACT OR GRANT NUMBER(s)
DAAG29-84-K-0158

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Rutgers-The State University of New Jersey
Mechanical & Aerospace Engineering Department
P.O. Box 909, Piscataway, NJ 08854

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

12. REPORT DATE
October 16, 1985

13. NUMBER OF PAGES
82

14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*

15. SECURITY CLASS. *(of this report)*
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*
NA

18. SUPPLEMENTARY NOTES
The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
Thermodynamic system analysis, Direct injection-type diesel engine, Temperature distribution in a piston, Control-volume finite element method, Successive differentiation, Transient conduction analysis of three-dimensional bodies

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

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Some results obtained from the present computational study are included in the report and the usefulness of the new computer program for the actual engine design is suggested herein. In addition, recommendation for improvement of the present computational model is included.

ARO 21770.4-EF

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Final Report

K. T. Rhee, X. L. Yang and S. L. Chang

October 20, 1985
(Reporting Period, 01 August, 1984 - 31 July, 1985)

U. S. Army Research Office

Contract Number, DAAG29-84-K-0158

Rutgers, the State University of New Jersey
College of Engineering,
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New Brunswick, New Jersey 08901

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by

K. T. Rhee, X. L. Yang and S. L. Chang

ABSTRACT

A thermodynamic system model of a direct injection-type diesel engine has been developed. The objective of the modeling was to enable predictions of the instantaneous temperature distribution along and into the combustion chamber of a diesel engine.

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STATEMENT OF PROBLEM

The recent adiabatic engine activities have greatly been enhanced by both excitement with the engine's superior performance and and difficulty of problems encountered in leading the new adiabatic engine concept to an engineering product. Technical problems with such stimulation have always been favorite targets of many researchers in the past. With juicy excitement in one hand and the difficulty in other hand, however, the problems may not be readily solved due to their special nature. For instance, the tribology problem of the new engine system, one of the most detrimental issues faced in its development, may be effectively solved only through interdisciplinary collaborations. A successful selection of material and its processing for the construction of the cylinder liner needs a careful analysis in various aspects, i.e., the surface temperature, the chemical composition of the working environment, etc. In particular, when the designer's choice is to employ a composite material for the liner, either its experimental or theoretical analysis (e.g., in the above aspects) becomes no simple task.

One of the more effective tools used by the engine designers under similar circumstances has been the computer simulation of the combustion system. Such an approach did not provide the exact answer to the problems but it did greatly save development costs in many cases. The pay-off of using computational methods will become greater when more realistic models are constructed in particular for the analysis of highly involved problems.

Most of the previous engine analysis models developed for a diesel engine are unable to predict space-resolved engine information, such as the temperature distribution over the piston crown. This was mainly due to the difficulties in developing meaning ful models of radiation and convection heat transfer processes. In addition, modeling of transient thermal conduction in engine components has been severely limited in the past compounding the said difficulties. The present work was under taken to facilitate the solutions of the issues delineated herein.

1. BACKGROUND

The high payoff development of diesel engine technology has become even more promising recently with the introduction of the innovative adiabatic diesel engine concept. U.S. activities in the adiabatic engine area, largely pioneered by TACOM, have brought about a significant technological transformation in the diesel engine.

A successful adiabatic (the term, "low-cooled" or "uncooled" may be more suitable, instead) engine is expected to offer tremendous advantages over the conventional diesel engine. The most important operational characteristics of the new engine may be its uncompromisingly high fuel efficiency, as demonstrated by a low-cooled diesel engine installed in a five-ton military truck which achieved a brake specific fuel consumption (bsfc) of 0.285 lb/hp-hr (Bryzik and Kamo, 1983). The bsfc is expected to attain up to 0.25 lb/hp-hr when the minimum friction ringless turbocompound adiabatic engine becomes available around the year 1995. This new concept of engine system certainly serves, to the authors' opinion, as a vitality injected into the currently rather sluggish progress of efficiency improvement in conventional diesel engines: at the beginning of their increasing popularity (in the late 1970's), diesel engine passenger cars provided about 29% higher fuel economy than similar cars with gasoline engines; the advantage of the diesel passenger cars, by 1983, decreased to only 20% relative to the gasoline engine-powered cars (Wade and Jones 1984). One of the more promising approaches to restoring the name of "diesel-efficient engine" is recommended to take the low-cooled turbocompound engine concept in the diesel engine. The need for improvement is equally recognized for large scale engines.

Among other comparably advantageous characteristics of the new system are the elimination of the cooling system, reduced size and weight, improved reliability, greater vehicle/engine design freedom, reduced noise, and greater fuel tolerance. Since these are important engine characteristics in meeting the propulsion system goal of the U.S. Army vehicle system, the central role of the Army in the U.S. low-cooled engine programs seems to be entirely justified. The principal merits of the new engine are extremely valuable in both commercial and military applications. For example, the use of the uncooled engine in a combat vehicle will reduce the engine size by 50%, the cooling system by 66%, and the fuel system by 40%, projecting a volume reduction of the total propulsion system by 39% (Glance and Munt, 1982). In addition, since up to 50% of the commercial and military engine field failures are related to the cooling system, the absence of a cooling system in the engine will greatly reduce the vulnerability of the vehicle system. Furthermore, since the new engine offers a high specific power density (hp/ft^3), the system is considered to be a strong candidate for replacing the high fuel

consumption gas turbine presently used in helicopters (Wilstead, 1982). It is expected the replacement will achieve more than a 42% bsfc reduction in existing helicopters.

The low cooled diesel engine which is an intriguing concept has created a world-wide challenge for engineers, i.e., solving the problems encountered in leading this concept to a finished engineering product. As implied by its name, the low cooled engine has the goal of controlling heat transfer in the system. This may be achieved by taking one of or a combination of the following: (1) proper development/selection of engine material, (2) creative design/combination of engine components, and (3) develop high-performance lubrication for the new engine operations. Since this goal is presently being achieved by the modification and/or redesign of the conventional direct injection type engine, it is an important requirement in the process of its development to properly evaluate the impact created by the new engine modification (here, the insulation and elimination of the cooling system) on the conventional engine's function and components. The results of the evaluation are expected to serve as decisive input in the selection of the component of material, design, and lubrication for achieving a better low cooled diesel engine. One of the more useful means of such evaluation was considered to employ a computational method: an extensive engine simulation model including the processes of cycle analysis, combustion, heat transfer, etc.

In the construction of a system analysis model of diesel combustion for predicting the temperature distribution in the engine parts comprising the combustion chamber, the following computational models that constitute the global model are needed.

(1) Engine cycle simulation model,
(2) Engine combustion model which provides the distribution of in-cylinder species,
(3) Conduction heat transfer model,
(4) Convection heat transfer model,
(5) Radiation heat transfer model, etc.

At the time when the present work was proposed, there were some activities being carried out by others in an attempt to achieve a similar goal to the present objectives. In spite of such others' work, it was decided to develop a new system analysis model in our laboratory because of the following reason: it was considered that our new radiation heat transfer model which had been constructed was the most advanced of the kind; and we have been carrying out the proposed study by developing other submodels in the above list. Further the proposed study was closely related with and comprises our ongoing engine combustion research at Rutgers, the objective of which was to obtain the relationship of radiation heat transfer to in-cylinder species distribution in a diesel engine.

2. OBJECTIVE

The objective of the present study was to construct a computational system analysis model of a direct injection-type diesel engine. The model was to enable prediction of the temperature distribution into and along the combustion chamber of a diesel engine made of composite material. The original goal of the model use was to implement the analysis by employing an IBM PC so that some handy analysis could be carried out was needed.

3. METHODOLOGY

Among the submodels of engine processes mentioned in the previous page are two submodels that were being developed by the time of its proposal in our laboratory. They were submodels of the engine cycle simulation and the radiation heat transfer process. In particular, the radiation model had actively been constructed on an ARO-supported sister project. They were in a usable condition but needed some work of debugging and adjustment for being included in the present global model of engine system analysis to be performed during the project period.

As an overall evaluation of the methodology taken in the present study, although we hoped to construct a global model of engine system analysis as perfect as possible during the project period, it turns out that we have taken an approach of achieving bilateral objectives in its development. One was a short-term goal to construct a new thermal conduction model, which has become the most interesting and intriguing result among those obtained in the present project. The key issue of the conduction model is a new numerical scheme, called "the control volume finite element method" developed on the present sponsorship. Because of our emphasis on its new numerical scheme due to its potentially extensive and great usefulness in various ways, the global model construction was made with inclusion of more assumptions than we originally planned for. Consequently, the construction of an more in-depth model of the combustion process was placed as a long-term goal to be implemented as a continuing activity in our laboratory. In describing the results obtained on the present sponsorship, the report is prepared in two parts:

(1) A detailed discussion of the new conduction model along with a brief description of other submodels, and

(2) Analysis of computational results obtained by using the present global model in predicting the temperature distribution in a piston of a direct injection-type diesel engine.

Note that an extensive manuscript, which will contain more details, is being prepared for the purpose of reporting in a technical society.

4. DESCRIPTION OF THE SYSTEM ANALYSIS MODEL

In order to construct a system analysis model of a diesel engine which enables the predictions of temperature distribution in the engine components of the combustion chamber and of the engine performance, several submodels need to be developed.

Combustion Process. The engine combustion process is in need of proper modeling. Its modeling may be achieved by modeling of various processes including the gas exchange (intake and exhaust) process, the fuel injection/atomization, mixing and vaporization, the gas motions, the chemical kinetics, etc. The construction of such a model is important and, on the other hand, is difficult to achieve: it is important to construct a model because, in a computation of heat transfer in the cylinder, for example, such a model will provide the source of heat, i.e., the temperature and species distributions; it is difficult to model the process due to so many unknowns and complexity of the various processes, i.e., modeling "unsteady heterogeneous reacting turbulence flows." Even with some success in modeling of gas motions, its coupling with the energy equation has been a difficult task to overcome. In spite of the difficulties, some success in its modeling is reported in recent literature (Amsden, et al., 1985). Again, the inclusion of such a model in our global model would have been highly desirable. Note that, however, the construction of such a model or an endeavor of combining an existing combustion model to a heat transfer model is a lengthy task requiring in-depth experience in modeling of the kind. Under the given limitations in time and resource faced in the proposed project, an approximation model of combustion process was to be developed for the global model. This choice included in the original plan was abandoned in order to concentrate our effort for a thorough study of heat transfer rather than diverting a part of the resource to construct a model which is sure to be obsolete even upon completion of its construction. Instead, assumptions were employed, which will be removed or minimized in a next study, for the global model as explained later.

Once the heat source, which may be characterized by the instantaneous distributions of temperature and species is known, a fairly extensive heat transfer computation can be made by using the present global model. The convection model may become straight forward, at least in theory, upon the completion of the combustion modeling: its validity will be as good as that of the combustion model. The radiation heat transfer modeling is one of the main parts for the global model. In addition, the conduction heat transfer model may be placed as the main program of the heat transfer model to predict the temperature distribution over the combustion chamber. Computational results from the other submodels may be introduced as the boundary condition of the main program.

RADIATION HEAT TRANSFER MODEL. Since the fraction of heat transfer through the radiation process out of the total heat loss in a typical direct injection type diesel engine may be 30% or more (Ebersole, et al., 1963), it is necessary to include the radiation heat transfer analysis in a system analysis of the engine. In particular, since the radiation heat transfer process is highly direction and spectrum dependent in nature, its proper analysis is needed in predicting the temperature distribution over a diesel engine combustion chamber. In view of its importance, a computational and experimental research project is being carried out at Rutgers under a separate sponsorship of ARO. A brief discussion is made on the modeling of radiation heat transfer in diesel combustion.

In implementation of a better analysis of radiation heat transfer in diesel combustion, several difficult problems are faced: Most serious problems to be solved in modeling the process may be listed as follows:

(1) A detailed description of distributions of combustion products and temperature in terms of a suitable coordinate system centered at individual locations over the combustion chamber wall. This information is necessary for finding the optical properties in the hemispherical volume faced by each location, which are used in solving the equation of radiation through individual optical paths with respect to the location.

(2) A viable computation of spectral volume absorptance of mixture of combustion products. This is required for processing the distributions mentioned in (2) to find the optical properties to be used in the governing equation of radiation to be mentioned later.

(3) A more accurate computational method for integrating the equation of radiation heat transfer along individual optical paths in the hemispherical volume as stated in (1).

In order to overcome the abovementioned difficulties the following methods were developed/employed: Mentioning the problem stated in (1), the species distribution was computed by using a new coordinate transformation technique developed in our laboratory (Chang and Rhee, 1985; a copy of its manuscript is included in Appendix-I). The key of the new method is to find, upon the species distribution (temperature distribution, as well) given in terms of a coordinate with respect to the injection nozzle, the species distributions along individual optical paths centered at any locations over the combustion chamber wall. Speaking of the issue explained in (2), the volume absorptance of combustion products were calculated for the range of radiation by using the Rayleigh limitation expression and a semiempirical band model in finding soot radiation and gas radiation, respectively. This is discussed in more detail in the abovementioned

manuscript. A better computational technique for solving the governing equation of radiation heat transfer was sought by using the Gaussian integration method (Chang and Rhee, being prepared for publication). More discussion on this is made in Appendix-I. Note that the results from the radiation heat transfer computation are needed for finding boundary conditions to be introduced in the conduction heat transfer computation.

CONDUCTION HEAT TRANSFER. Since this subject carries a more weight than others in the present report, a separate chapter is assigned for its extensive discussion as follows.

5. THREE-DIMENSIONAL CONDUCTION HEAT TRANSFER MODELING FOR CYLINDRICAL SHAPE BODIES

The problem of finding the heat transfer and temperature distributions in the combustion chamber has long been studied. It is important to have the distributions because the engine manufacturers face strong needs of a proper thermal loading analysis of engine parts composing the combustion chamber. A number of approaches were taken to measure and predict the temperature distribution in such complex geometry components. Discussing the experimental method, in 1964, Whitehouse et al. measured the variation in a piston crown. He found that the fluctuation in temperature at the surface was rapidly reduced to steady states within the depth of a few milimeters of the surface. Woschini and his coworkers (1967; 1979; 1979) measured the temperature of a piston at 20 discrete points and evaluate the entire steady state temperature distribution by using both the relaxation method and electrolytic tank analysis. Regarding the computational analysis, the finite element method has often been employed to obtain the temperature distributions. Saursten (1979) and Saugerud and Sandsmark (1979) assumed a steady steady axisymmetric thermal boundary condition and calculated the distribution in a piston. They also attempted a comparison of a two-dimensional computation and results measured from a real three dimensional case. Recently, Morel et al. (1984) used a one-dimensional transient conduction code to analyze the temperature fluctuation in a thin layer of the combustion chamber and used the finite element method to calculate the steady state temperature distribution inside the chamber wall. Completing a literature survey, it is found that there has not been any suitable three-dimensional transient conduction analysis conducted for the engine components. For example, the number of engine cycles from the start of an engine until various critical places in its combustion chamber reach steady state temperature has not been properly evalyuated. Recognizing that such a piece of information is of great value for accessing the engine' thermal loading, a new extensive was developed by taking the following approaches.

(1) A new control volume finite element method that holds the merits of both the finite element and finite difference methods was developed.

(2) A successive differential method in time domain was employed to obtain more accurate and stable solutions.

(3) A new computer aided automatic mesh generation program which expedites the implementation of the model was developed.

The new conduction model was developed to be placed as the main program in the present global analysis of heat transfer in an engine. Results computed from other submodels are introduced into the main program as boundary conditions. In the present study, the time- and space-resolved temperature distribution in a diesel engine piston was calculated by using the boundary conditions, as mentioned in Chapter 4. Further details of the processes taken to obtain this are explained in the following.

A. DESCRIPTION OF THE NEW CONDUCTION ANALYSIS METHOD

The problem given here is to find the instantaneous temperature distribution in the engine parts of a direct injection type diesel engine when boundary conditions are known. The geometry of the engine components is highly irregular in shape and due to the stratification nature of combustion reactants and products, the boundary conditions vary with location and time. Such boundary conditions are sought in other submodels as previously mentioned.

The general heat conduction problem with no heat generation in a region, R, enclosed by a boundary is governed by the following differential equation.

$$\rho c \frac{dT}{dt} + \vec{\nabla} \cdot \vec{q} = 0 \qquad (1)$$

where, $\vec{q} = -k\nabla T$, ρ is the mass density if material, c is the specific heat and k is the thermal conductivity. The dependent variable, T is continuous in R, and quantities ρ, c and k are uniform in each subregion of R. There may be interfaces at which ρ, c and k are discontinuous as long as the heat flux and temperature are continuous over the interface. What has been don here is to develop a new numerical technique written in a computer program to analyze an unsteady three-dimensional conduction process as expressed by Eq. (1). in engine components with cylindrical geometry. In order to solve the stated problem the following tasks were carried out.

(a) Automatic Mesh Generation,
(b) Control Volume Approach,
(c) Matrix Formation and Manipulation, and
(d) Solution of the Discritization Equation.

Automatic Mesh Generation in Two-dimensional Plane. One of the first steps to be taken in numerical analysis of heat conduction may be the generation of meshes in the computation domain with appropriate nodal points representing the individual nodal elements. Often, this process is tedious and prone to generate errors: development of a computer aided mesh generation technique was highly desirable to use in our work so as to handle elements with complex geometry. The technique sought was required to meet the following criteria:

(1) Adequate boundary description indicating if connected singulary or multiply;
(2) Means to identify material properties in each node;
(3) Acceptable resolution and accuracy;
(4) Easy bookkeeping of coordinate of nodes; and
(5) Easy graphical presentation by using a plotter.

A new mesh generation technique has been developed in a direction to meet the above requirement as much as possible. The program was written in Basic language to be used in an IBM PC connected to an HP 7475 plotter to handle elements with two-dimensional region. Since our new numerical scheme utilizes nodal elements with triangular geometry, the mesh generation was made to meet this purpose.

The essence of the automatic mesh generation scheme is the use of piecewise connection of successive lines from nodal point to nodal point in order to triangulated the computation domain. Consider a typical geometry of substance of heat transfer which is to be divided into nodal elements over the entire domain as shown in Fig 1. The domain geometry may be either irregular or regular. The domain will be divided into quadrangular elements with more likely uniform sizes with its points along the boundary contour successively connected. Subsequently, the quadrangle is divided into two triangular elements, in either way as shown in elements P and Q of Fig. 1.

One of the main input data is a set of sufficient number of coordinates showing the points to describe the boundary contour of the domain. The only requirement is the number of points to be specified have to equal each other in both sides and both ends, respectively; the number in one side does not need to be the same as that in one end, however. In determining the elements of quadrangle with relatively uniform sizes in the domain the following method is employed. By taking an arbitrary node (i,j), one may define the following new numbers.

$$r_{1i} = (x_{1,j} - x_{1,1})/(x_{1,n+1} - x_{1,1})$$

$$r_{2j} = (x_{m+1,j}) - x_{m+1,1})/(x_{m+1,n+1} - x_{m+1,1})$$

$$s_{1i} = (y_{i1} - y_{m+1,1})/(y_{1,1} - y_{m+1,1})$$

$$s_{2j} = (y_{i,m+1} - y_{m+1,n+1})/(y_{1,n+1} - y_{m+1,n+1})$$

where, m is the total number of points in one side and n is the number of points along one end. The determination of nodal points (x_{ij},y_{ij}) within the contour of the substance are determined by using the following formulas:

$$r_{ij} = r_{1j}\ (m + 1 - i)/(m + r_{2j}\ (i - 1))/m$$

$$s_{ij} = s_{1j}\ (n + 1 - j)/(n + s_{2j}\ (j - 1))/n$$

$$x_{ij} = (1\ r_{ij})\ x_{i1} + r_{ij}\ x_{in}$$

$$y_{ij} = (1 - s_{ij})\ y_{1,j} + s_{ij}\ y_{1j}.$$

During the process of developing the computer-aided mesh generation by taking the above method, several refinements were made for its uses in analysis of various geometries. Among the significant refinements is a special caution for the case with right-angled corners of the domain to be meshed. Without this, in such a case, multiply defined points or ill-conditioned elements (e.g., triangles with zero area) were encountered. An example of results from the automatic mesh generation is shown in Fig. 2. The number in each nodal point indicates the corner characteristics which determines a pertinent numerical scheme as explained later. Without mentioning the details, note that the characteristic numbers are determined in the program which governs the energy conservation equation to be explained later.

Modal Elements in Cylindrical Shape Elements. For the determination of nodal elements in cylindrical bodies, the r-z plane of the component was divided into triangular elements by using the abovementioned two-dimensional method. Upon the determination of meshes in r-z plane, the component was divided in the circumferential direction as shown in Fig. 3.

B. CONTROL VOLUME FINITE ELEMENT METHOD.

Since the exact solution of Eq. (1), in general, is not readily available if the geometry of the domain becomes complex,

numerical methods are employed, e.g., the finite difference method, the finite element method and the control volume method. Although the logic and algebra of the finite difference method are simple, its discrete node elements of which geometry is limited to square geometry often lack in resolution, e.g., the incomplete meshes near the sharp corner boundaries. The differential equation, Eq. (1), for such incomplete meshes have to be approximated for every individual case making its computer program of general use. The finite element method, on the other hand, can deal with irregular geometries, since it employs triangular elements opposed to the square elements in the finite difference method. Mathematically, the finite element method is based on variational formulation or Gallichin weighted integral formulation (Shin, 1984). The mathematical formulation, however, is rather involved and makes the computer program much more complex than that of the finite difference method. Further, its physical interpretation is not as clear as its counterpart in the finite difference method. This shortcoming often outweighs its advantages in particular when used in two-dimensional analysis: its advantage may be recognized in analysis of three-dimensional problems.

In the present work, a control volume formulation is employed. It combines the advantages of both the finite difference and finite element methods in dealing with the domains with irregular geometry in a simple manner. The control volume approach is based on the conservation of thermal energy. The method is based on the numerical balance of thermal energy over small subelements within individual nodal elements, consequently over the entire computation domain. This is achieved by starting from an integral conservation statement: again, the statement applies locally and globally.

An integral equation can be obtained based on Eq. (1) over a domain as

$$\frac{\partial}{\partial t}\int_{\mathcal{R}} \rho c T d\mathcal{R} + \int_{\sigma} \vec{q}\cdot\vec{n} d\sigma = 0 \qquad (2)$$

where, $\mathcal{R}$ is the region being considered and σ is the boundary of the region. From the integral equation, we can derive the discretization equation for each element. The basic procedure of deriving the discretization equation of the present method are,

(1) discretize the calculation domain into elements of certain geometric shape,
(2) use the element based interpretation function,
(3) derive the discretization equations by using the control volume method, and
(4) Compilation of coefficients in the discritization for all the elements.

Two-dimensional Discretization and its Equations. The discretization of the calculation domain in a two-dimensional plane is made as follows. As mentioned previously, the domain is divided into triangular elements. Consider a collection of the elements in the plane as shown in Fig. 4-(a). The element again divided into three-node elements by joining any of the midpoints of its side as shown in Fig. 4-(b). A typical triangular element with its subelements will, then, become one as shown in Fig. 5. Upon the determination of the triangular elements and their subelements, the integral conservation statement is applied to each of the three subelements. When applied, the integral equation for each subelement becomes

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_1} \rho c T d\mathcal{R} + \int_{\sigma_{12}} \vec{q}.\vec{n}d\sigma + \int_{\sigma_{13}} \vec{q}.\vec{n}d\sigma$$
+(similar contributions from other subelements associated with node 1)+(boundary conditions, if applicable)=0 (3)

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_2} \rho c T d\mathcal{R} + \int_{\sigma_{21}} \vec{q}.\vec{n}d\sigma$$
+(similar contributions from other subelements associated with node 2)+(boundary conditions, if applicable)=0

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_3} \rho c T d\mathcal{R} + \int_{\sigma_{31}} \vec{q}.\vec{n}d\sigma$$
+(similar contributions from other subelements associated with node 3)+(boundary conditions, if applicable)=0

The integrands in Eq. (3) are approximated based on averaged thermal properties, e.g., $k_{ij} = 2\, k_i\, k_j / (k_i + k_j)$. The above equations, therefore, are rewritten as follows.

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_1} \rho c T d\mathcal{R} = \rho_1 c_1 \mathcal{R}_1 \frac{dT_1}{dt}$$

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_2} \rho c T d\mathcal{R} = \rho_2 c_2 \mathcal{R}_2 \frac{dT_2}{dt}$$

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_3} \rho c T d\mathcal{R} = \rho_3 c_3 \mathcal{R}_3 \frac{dT_3}{dt} \qquad (4)$$

$$\int_{\sigma_{12}} \vec{q}.\vec{n}d\sigma = A_{12} k_{12} \frac{T_1 - T_2}{DR_{12}}$$

$$\int_{\sigma_{12}} \vec{q}.\vec{n}d\sigma = A_{12}k_{12}\frac{T_1 - T_2}{DR_{12}}$$

$$\int_{\sigma_{21}} \vec{q}.\vec{n}d\sigma = A_{21}k_{21}\frac{T_2 - T_1}{DR_{21}}$$

$$\int_{\sigma_{31}} \vec{q}.\vec{n}d\sigma = A_{31}k_{31}\frac{T_3 - T_1}{DR_{31}}$$

In these equations, A_{ij} represents the vertical area between the subvolume i and j; D_{ij} denotes for the distance between the subelements i and j as defined in the following.

$$DR_{ij} = [(x_i - x_j)^2 + (y_i - y_j)^2]^{1/2}.$$

Introducing these approximation terms into the conservation equation to individual nodal points, the integral conservation equation of the corresponding triangular element becomes, for example, with respect to node 1,

$$\frac{\partial}{\partial t}\int_{R_1} \rho cTdR + \int_{\sigma_{12}} \vec{q}.\vec{n}d\sigma + \int_{\sigma_{13}} \vec{q}.\vec{n}d\sigma = a\frac{dT}{dt} + c_1T_1 + c_2T_2 + c_3T_3 \qquad (5).$$

Regarding the elements composing the boundary of the domain, the domain is declared to hold a specific temperature of heat flux replacing a term in the above equation. The above equation can be written, in a straightforward manner in the computer program, for the entire elements in the domain with inclusion of appropriate boundary conditions. What has to be done, completing this step, is to solve the simultaneous unsteady equations for finding temperature values at individual nodal points, which will be explained later.

Three-Dimensional Discretization and Discritization Equations. Although an extension of the present two-di»ensional analysis may be made for solutions of three-dimensional domain by using the tetrahedral element. Upon a brief evaluation of this approach, it was found that there are a number of problems to be overcome in making the ideal of practical use, which is presently being studied in our laboratory. On the other hand, since most of the engine elements comprising the combustion chamber are axisymmetric, a new method has been developed for analysis of such objects, which is considerably simple to implement.

The basic idea of the present new method to analyze three-dimensional objects is as follows: first of all, the r-z

pane of the cylindrical coordinate centered at the axis of a cylindrical three-dimensional domain is discritized by using the previously mentioned new numerical scheme developed for the two-dimensional domain, and next the circumferential direction of the domain is discretized by appropriate increments. Two kinds of typical building blocks of nodal elements for this method are shown in Fig. 6. The elements were divided into six subelements in the corresponding nodal points and the discretization equations of energy conservation are written. The elemental equations for those subvolumes are listed in the following.

$$\frac{\partial}{\partial t}\int_{R_1} \rho c T dR + \int_{\sigma_{12}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{13}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{14}} \vec{q}.\vec{n} d\sigma$$
+(similar contributions from other subelements associated with node 1)+(boundary conditions, if applicable)=0

$$\frac{\partial}{\partial t}\int_{R_2} \rho c T dR + \int_{\sigma_{21}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{25}} \vec{q}.\vec{n} d\sigma$$
+(similar contributions from other subelements associated with node 2)+(boundary conditions, if applicable)=0 (6).

$$\frac{\partial}{\partial t}\int_{R_3} \rho c T dR + \int_{\sigma_{31}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{36}} \vec{q}.\vec{n} d\sigma$$
+(similar contributions from other subelements associated with node 3)+(boundary conditions, if applicable)=0

$$\frac{\partial}{\partial t}\int_{R_4} \rho c T dR + \int_{\sigma_{41}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{45}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{46}} \vec{q}.\vec{n} d\sigma$$
+(similar contributions from other subelements associated with node 4)+(boundary conditions, if applicable)=0

$$\frac{\partial}{\partial t}\int_{R_5} \rho c T dR + \int_{\sigma_{52}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{56}} \vec{q}.\vec{n} d\sigma$$
+(similar contributions from other subelements associated with node 5)+(boundary conditions, if applicable)=0

$$\frac{\partial}{\partial t}\int_{R_6} \rho c T dR + \int_{\sigma_{63}} \vec{q}.\vec{n} d\sigma + \int_{\sigma_{64}} \vec{q}.\vec{n} d\sigma$$
+(similar contributions from other subelements associated with node 6)+(boundary conditions, if applicable)=0

Using a similar approximation as that in the previously mentioned two-dimensional analysis, one can write the integral terms in the above equation in the following concise form:

$$\frac{\partial}{\partial t}\int_{\mathcal{R}_i} \rho c T d\mathcal{R} = \rho_i c_i \mathcal{R}_i \frac{dT_i}{dt} \qquad (i=1,2\cdots6)$$

$$\int_{\sigma_{ij}} \vec{q}.\vec{n}d\sigma = A_{ij}k_{ij}\frac{T_i - T_j}{DR_{ij}} \qquad (i,j=1,2\cdots6) \tag{7}.$$

Note that this equation is applied to the entire elements with appropriate boundary conditions. In Eq. (7), A_{ij} is the area normal to the direction through which heat flow from subcontrol volume i to j and DR_{ij} is the distance between the two. Consequently, a linear ordinary differential equation can be established for individual subelements associate with the corresponding nodal point. It is further found that the final form of the discretization equation for temperature at nodal point i, T_i, becomes,

$$\frac{dT_i}{dt} = \sum_n a_n T_n + b_{i0} + b_{i1}t \tag{8}$$

where the summation is made over all nodes pertinent to subelements associated with node i.

Solution Algorithm. In solving simultaneous unsteady ordinary differential equations, expressed as a form of Eq. (8), the equations are reduced to matrix form as follows,

$$\bar{u}' = \bar{A}\,\bar{u} + \bar{B}[\bar{u}_b + \bar{u}_b' t]$$

$$\bar{u}(t_c) = \bar{u}_o \tag{9}.$$

Although there are several methods to solve such equations, one way of increasing accuracy and stability in time marching is to employ "high order approximation" by using the successive differentiation method. Without showing the details of its derivation, the result of the present successive differentiation method is shown in the following.

$$\bar{u}' = \bar{A}\,\bar{u}+\bar{B}(\bar{u}_b+\bar{u}_b't)$$

$$\bar{u}'' = \bar{A}\,\bar{u}'+\bar{B}\,\bar{u}_b'=\bar{A}(\bar{A}\,\bar{u})+\bar{A}\,\bar{B}(\bar{u}_b+\bar{u}_b't)+\bar{B}\,\bar{u}_b' \qquad (10).$$

$$\bar{u}''' =\bar{A}\bar{u}'' =\bar{A}^2\bar{u}' +\bar{A}\bar{B}\bar{u}_b'=\bar{A}^3\bar{u}+\bar{A}^2\bar{B}(\bar{u}_b+\bar{u}_b't)+\bar{A}\bar{B}\bar{u}_b'$$

$$\cdots\cdots\cdots\cdots\cdots\cdots$$

$$\bar{u}^{(i)}=\bar{A}\bar{u}^{(i-1)}=\bar{A}^i\bar{u}+\bar{A}^{i-1}\bar{B}(\bar{u}_b+\bar{u}_b't)+\bar{A}^{i-1}\bar{B}\bar{u}_b'$$

$$\bar{u}(t)=\bar{u}_o+(\bar{A}\bar{u}_o+\bar{B}\bar{u}_b)t+\sum_{i=2}^{n}\frac{\bar{A}^i}{i}\bar{u}_o t+\frac{\bar{A}^{i-1}\bar{B}}{i}\bar{u}_b t^i+\sum_{i=2}^{n}\frac{\bar{A}^{i-2}\bar{B}}{i}\bar{u}_b t^i \quad . \quad .$$

6. COMPUTER PROGRAM FOR THE CONTROL VOLUME FINITE ELEMENT METHOD BY USING THE SUCCESSIVE DIFFERENTIATION

A new computer program has been developed utilizing the new concept of the present control volume finite element method by using a numerical scheme of the successive differentiation. The program was written in FORTRAN language and a name was given as "HEATRAN." The HEATRAN program of the heat conduction analysis along with its flow chart is included in Appendix-II, where the entire global model of heat transfer analysis is included.

7. PREDICTION OF TEMPERATURE DISTRIBUTION IN A DIESEL ENGINE PISTON

The present global model which includes several submodels, e.g., a conduction model and radiation heat transfer model, was used for predicting the temperature distribution in a diesel engine piston. The following assumptions were employed in the computation:

(1) The instantaneous space averaged heat flux through the piston top surface is given as shown in Fig. 7.

(2) Of the heat flux history in Fig. 7, the distribution of instantaneous heat flux during the period, 350 - 400 crank angle (CA), however, is space-resolved as follows: the distribution in r-direction is given in the form as shown in Fig. 8, and the distribution in circumferential direction is of normal distribution. The integrated total heat flux at each engine crank angle given in the abovementioned way is equal to that in corresponding engine crank angle shown in Fig. 7.

(3) The total heat flux can be dissolved into portions of those through radiation and convection processes in either ways as shown in Fig. 8 or Fig. 9.

(4) The piston is made of aluminum.

(5) The cut-view of r-z plane of the piston is shown in Fig. 2 and it is axisymmetric.

(6) The side of the piston is insulated. The bottom surface of the piston is maintained at 400 deg K. The piston was initially at 400 K.

(7) The engine is of direct-injection type and has four identical spray plumes with distributions of radiatively participating species, F, expressed in Eq. (8) in Appendix-I. The engine has minimum swirl motions.

The reasons for employing the assumptions may be explained in the following. The instantaneous heat flux through the piston top surface in diesel combustion is not properly known, although some measurements and predictions have been reported, e.g., those by Whitehouse (1970). Some active study is carried out in our laboratory for helping improve our understanding of the process. Regarding the fractions of heat fluxes contributing either convection or radiation process, the basic unresolved issue is the unavailability of in-cylinder species distribution. Since there are two different kinds of radiation heat transfer flux distribution considered in literature (Chang, Yang and Rhee, 1985; Chang, Kobayashi and Kamimoto, 1985) the present computation was carried out for both cases (Fig. 8 and 9). The rest of the assumptions can clearly be replaced by more dependable input boundary conditions for the main program. More realistic computations are being planned in our laboratory.

For reference, note that the computing time required for a semi-steady state computation starting from the initial condition was about five hours when an AS/9000 computer located at Rutgers was used: the results shown in this report are those obtained after completing computation of about 700 cycles of the engine operation at a speed of 1,000 rpm.

Instantaneous Temperature at Various Locations on the Top of Piston. The temperature history computed based on the heat flux input shown in Fig. 8 is shown for various locations at the piston top (Figs. 10, 11 and 12). Note that the computed temperature results are shown in a nondimensional value, T, defined as $\bar{T} = (T - 400) / 400$. The small section of figure in Fig. 10 and some of the other figures herein presented indicates the locations in the piston top of the corresponding temperature history. While the peak input heat flux is given at $r/R = 0.5 - 0.8$, the highest temperature level was found to occur at similar locations, which may be expected. When histories of both heat flux and temperature are compared, it is found that there is a delay in rise of temperature by about 50 degrees of CA from the

rise in the input heat flux. Such a lag in temperature rise is a typical example of the transient conduction problems. Further analysis is needed on this problem because of its importance in evaluating the thermal loading on the piston.

Surface Temperature Distribution over the Piston Top Surface. Figure 11 shows the space-resolved temperature distribution plotted for engine crank angle of 400. This is a time before the peak temperature is reached on the piston top so that the surface distribution continues to change as seen in Fig. 10. After brief look at Figs. 10 an 11, one can readily find that there is relatively small variation of temperature level in circumferential direction although the heat flux input was given in a normal distribution in the direction (see assumption-(2) shown in the previous page). This may be due to both the high thermal conductivity of piston piston material (aluminum) and the rapid heat flows contributed by two spray plumes into the space with low heat input located between them (consider the valley between two normal distributions of heat input). The temperature distribution along the direction of axis of the plume, i.e., the radial direction of the piston is shown in another form at engine crank angle of 400 as shown in Fig. 12. The results in this figure show that the peak in temperature does not correspond to the peak found (see point A in Fig. 10) in the later engine crank angle. Note however when a computation was made for the heat input given as Fig. 9, which has higher radiation heat flux near the injection nozzle, the peak of the temperature was found correspondingly near the nozzle as well (see Fig. 13).

Temperature Distribution in an r-z Pane of the Piston. Without any particular reason, again the results computed for engine crank angle of 400 were plotted in order to show the temperature distribution in r-z plane of the piston. The temperature distribution near the rings and piston bowl curves are of high detail. Computational results were plotted for the heat input given in Figs. 8 and 9, for comparison purpose, as shown in Figs. 14 and 15, respectively. Note that such information can be readily evaluated for the pistons having the ceramic piston cap presently used in the uncooled diesel engine. It is further noted that when more realistic heat flux input becomes available for the locations near the piston rings, some useful design information may be derived by using the present model.

8. SUMMARY AND RECOMMENDATIONS

A preliminary thermodynamic system analysis model of a direct injection-type diesel engine has been constructed. Among the significant achievements made in the present project are (1) development of a new numerical method of transient conduction heat transfer analysis, (2) an introduction of the successive differentiation method in time-marching in search of its numerical solution, (3) construction of a computer aided mesh generation program, (4) an analysis of temperature distribution into and over a diesel engine piston, etc. Further improvement of the present model is being carried out and at the same time more in-depth analysis of the temperature distribution in other engine component of the engine combustion chamber is carried out.

Since the computation of the temperature distribution in engine components of the chamber is made based on the results from the radiation heat transfer and species distribution in the combustion chamber, the accuracy of temperature analysis is obviously dependent upon their results. The logical consequence, therefore, is that there is an absolute need in improving the computation to obtain those results.

It is recognized that due to the complexity and scale of the undertaken project (consider that the computer time for a simple analysis by using our program in an AS/9000 was about five hours) a long-term support for it is needed. It is felt that completion of the present contract simply serves as a starting point for both further analysis of the temperature distribution and construction of a better global heat transfer model of a diesel engine.

Since the results shown in the report may be a mere demonstration to show what the present model can do for achieving a better analysis of an engine's heat transfer, any concluding technical remark on its process may be somewhat premature. Nevertheless, we believe that our new model of engine heat transfer analysis can profitably be used even in the present form although there is a lot of room for improvement.

9. ACKNOWLEDGMENT

The present work was proposed to conduct on the strong encouragement by Dr. Walt Bryzik of U.S. Army Tank Automotive Command (TACOM). The entire course of the study was closely monitored by Dr. David M. Mann, U.S. Army Research Office. Mr. Ernest Schwarz of TACOM served as scientific liason representative on the project. Their interests and suggestions on the work are greatly appreciated.

10. LIST OF PUBLICATIONS AND TECHNICAL REPORTs

Presently, two manuscripts are being prepared for publishing in professional journals.

11. PARTICIPATING SCIENTIFIC PERSONEL

The following individuals have contributed in carrying out the present project:

Professor K. T. Rhee, Principal Investigator

Dr. S. L. Chang, Researcher, and

Mr. X. L. Yang, Graduate Student.

Mr. Yang is scheduled to have his final examination for his M.S. degree which has been pursed on a partial finalcial support from the present contract.

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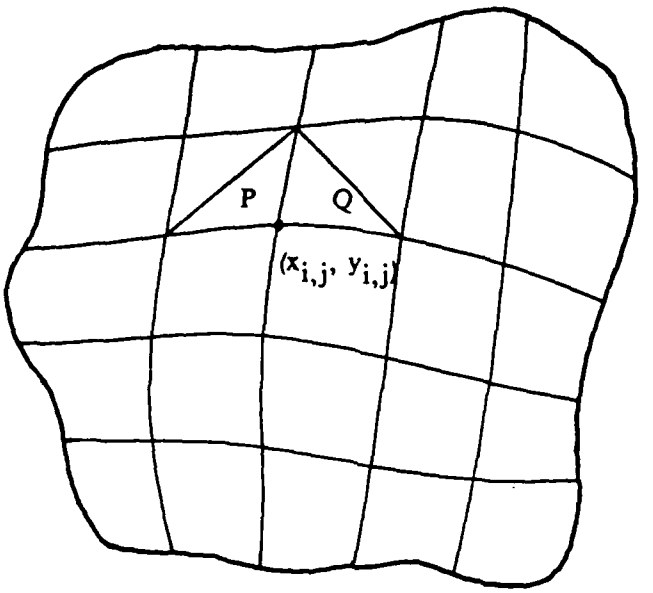
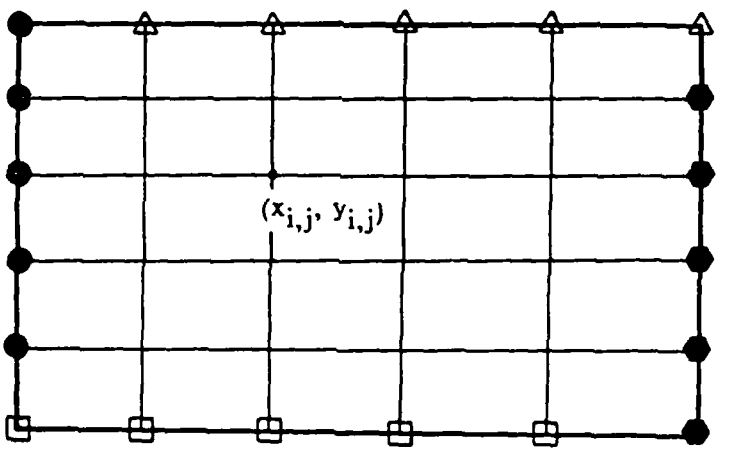


(a)



(b)

Fig. 1 The Basic Concept of the New Mesh Generation Technique:
(a) Irregular Shape Region, and
(b) Regular Shape Region.

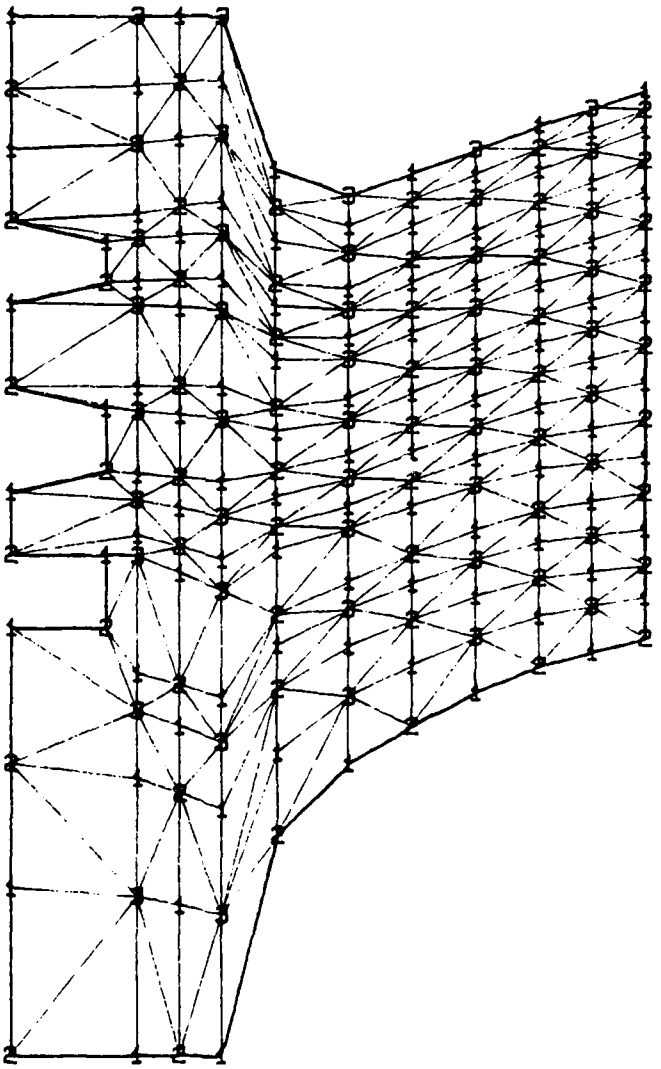


Fig. 2 Mesh Generation for a R-Z Plane of an Engine Piston

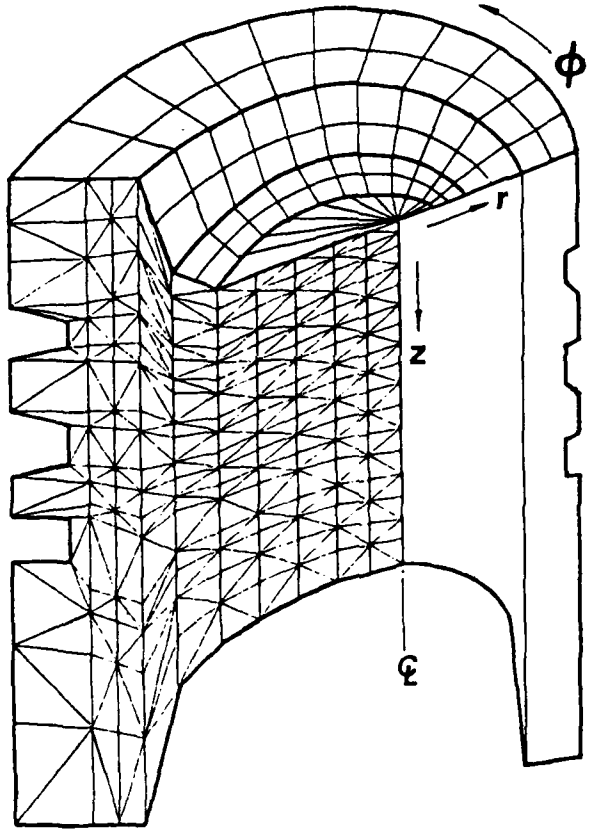


Fig. 3 Discretization of An Engine Piston

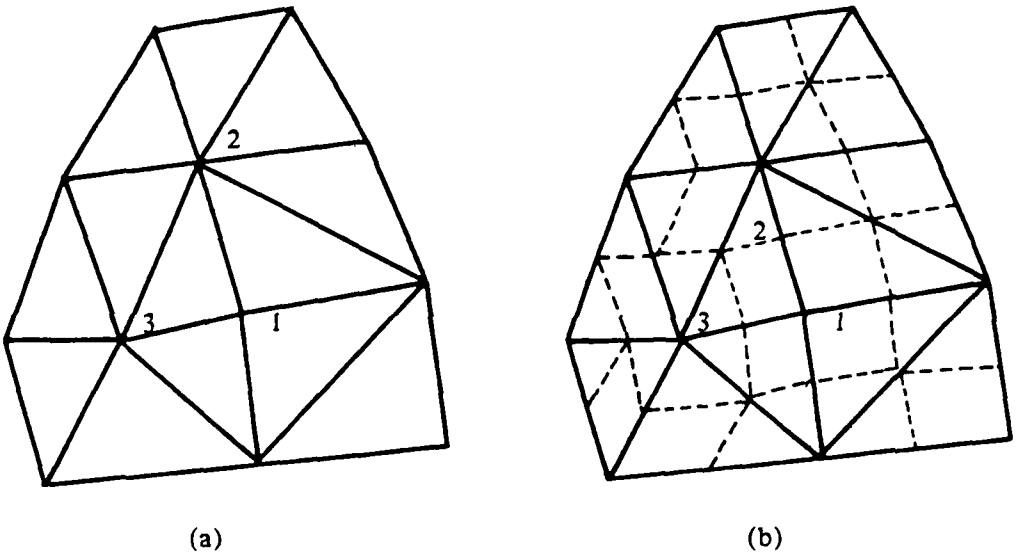


Fig. 4 An Irregular Shape Calculation Domain and Its Discretization (a) A Triangular Element and (b) Subcontrol Volumes

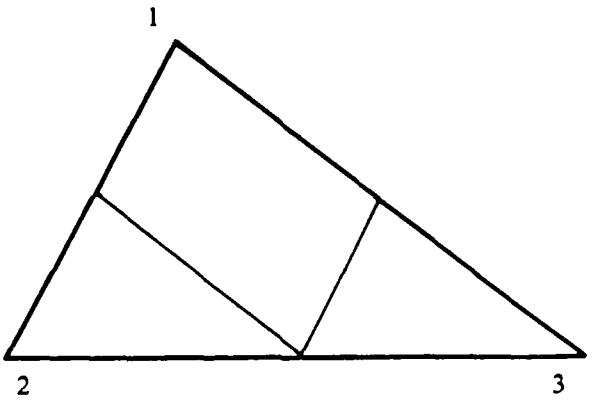
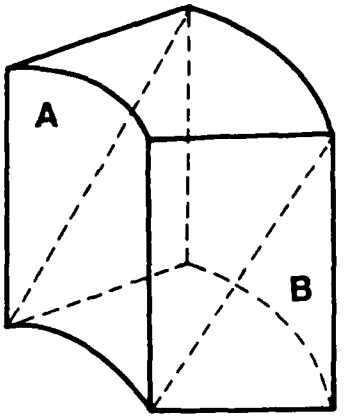
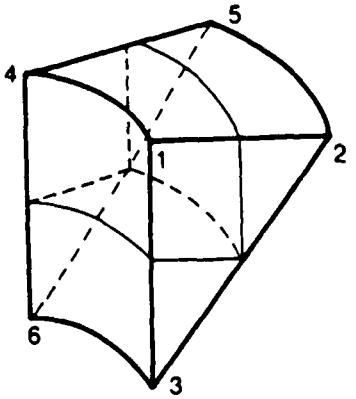
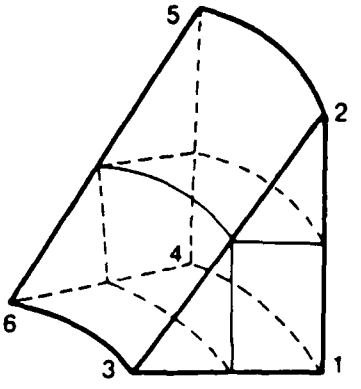


Fig. 5 A Typical Triangular Element and Its Three Subelements





(A)



(B)

Fig. 6 Two Typical Nodal Elements in Discretization for 3-dimensional Computation

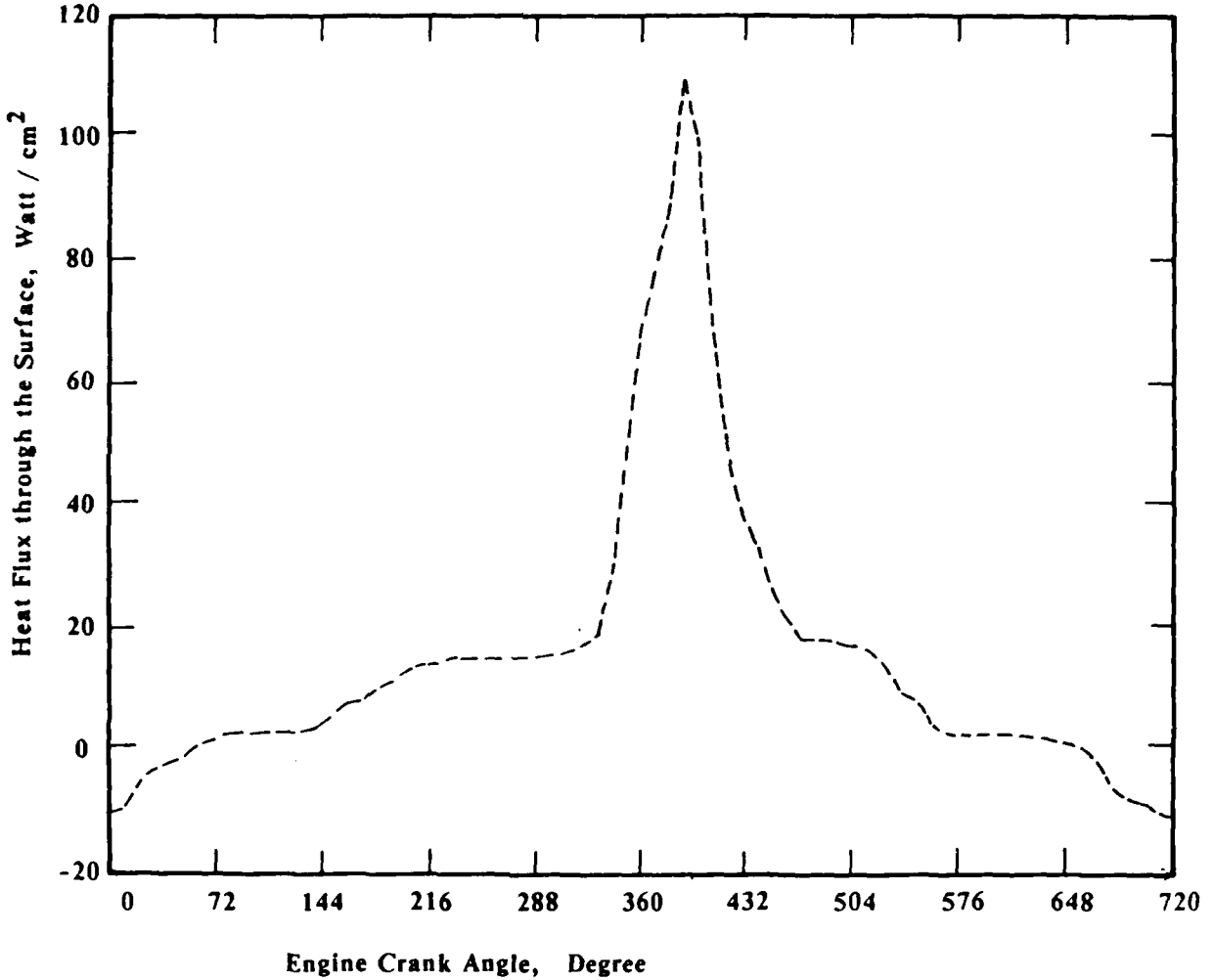


Fig. 7 Instantaneous Uniform Heat Flux through the Piston Top Surface (The Reaction Period, 350 - 400 CA, Spatial Heat Distribution: ϕ-direction, Normal Distribution; r - direction, see Fig. 12).

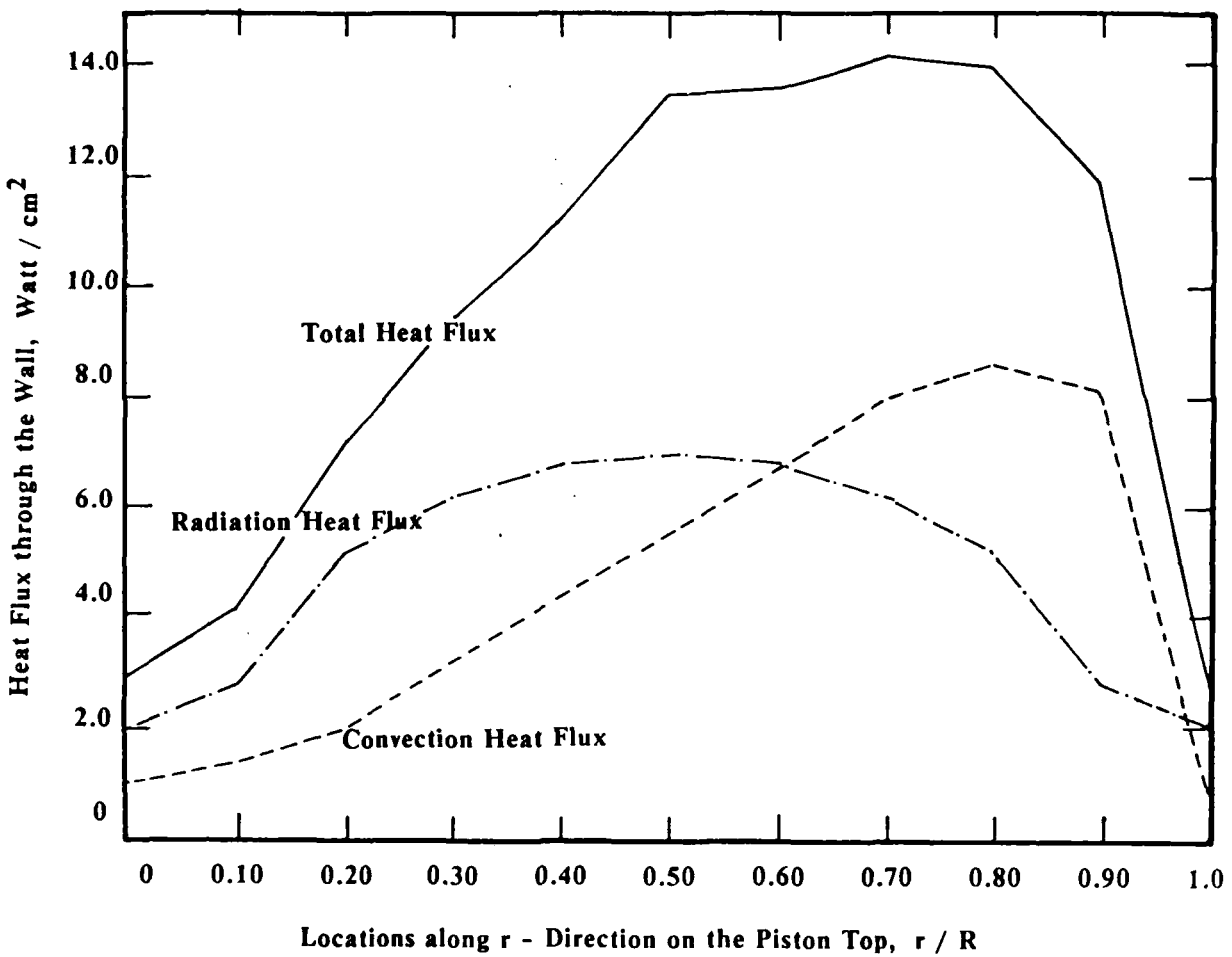


Fig. 8 Heat Flux through Locations along r - Direction on the Piston Top at Engine Crank Angle of 400.

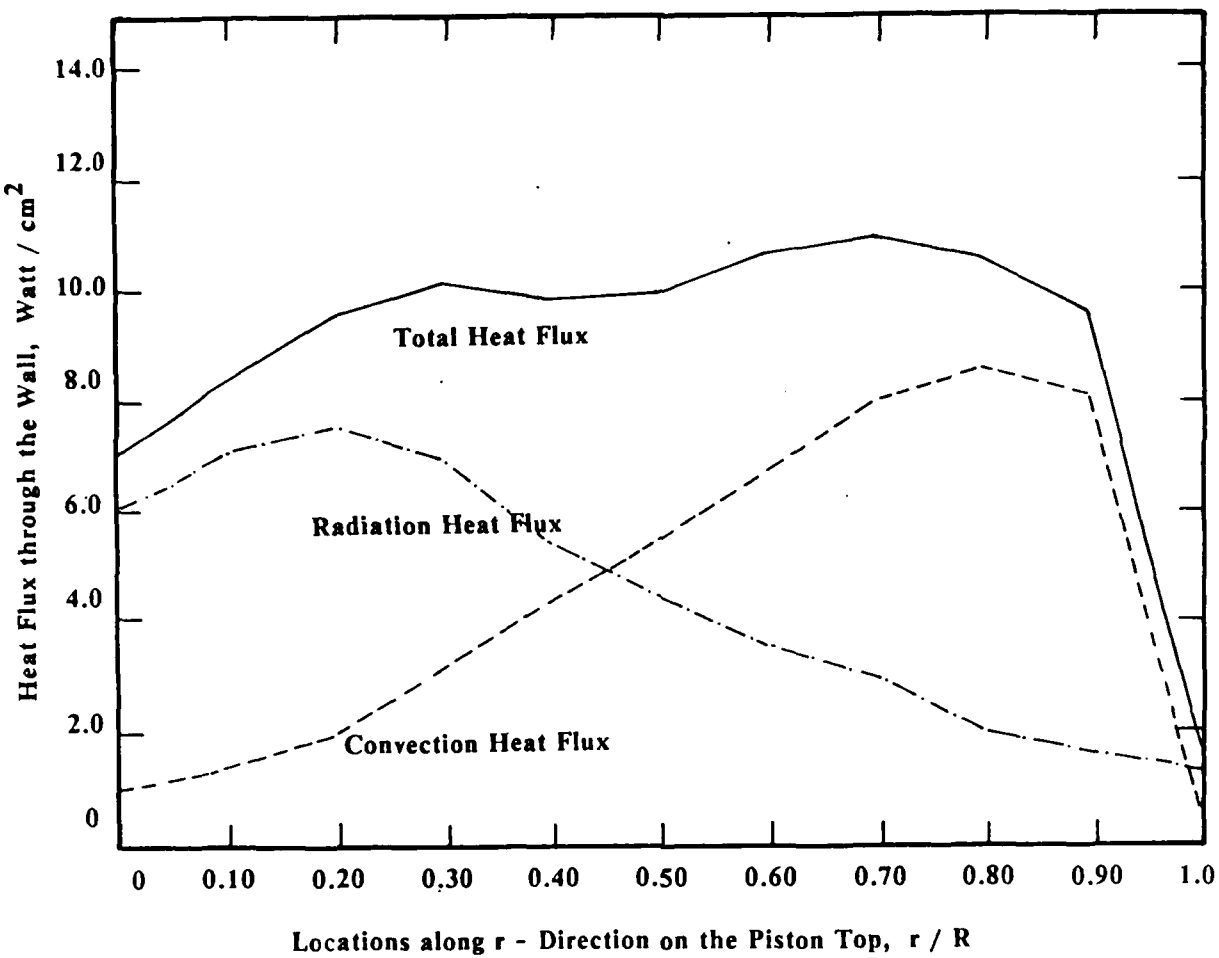


Fig. 9 Heat Flux through Locations along r - Direction on the Piston Top at Engine Crank Angle of 400.

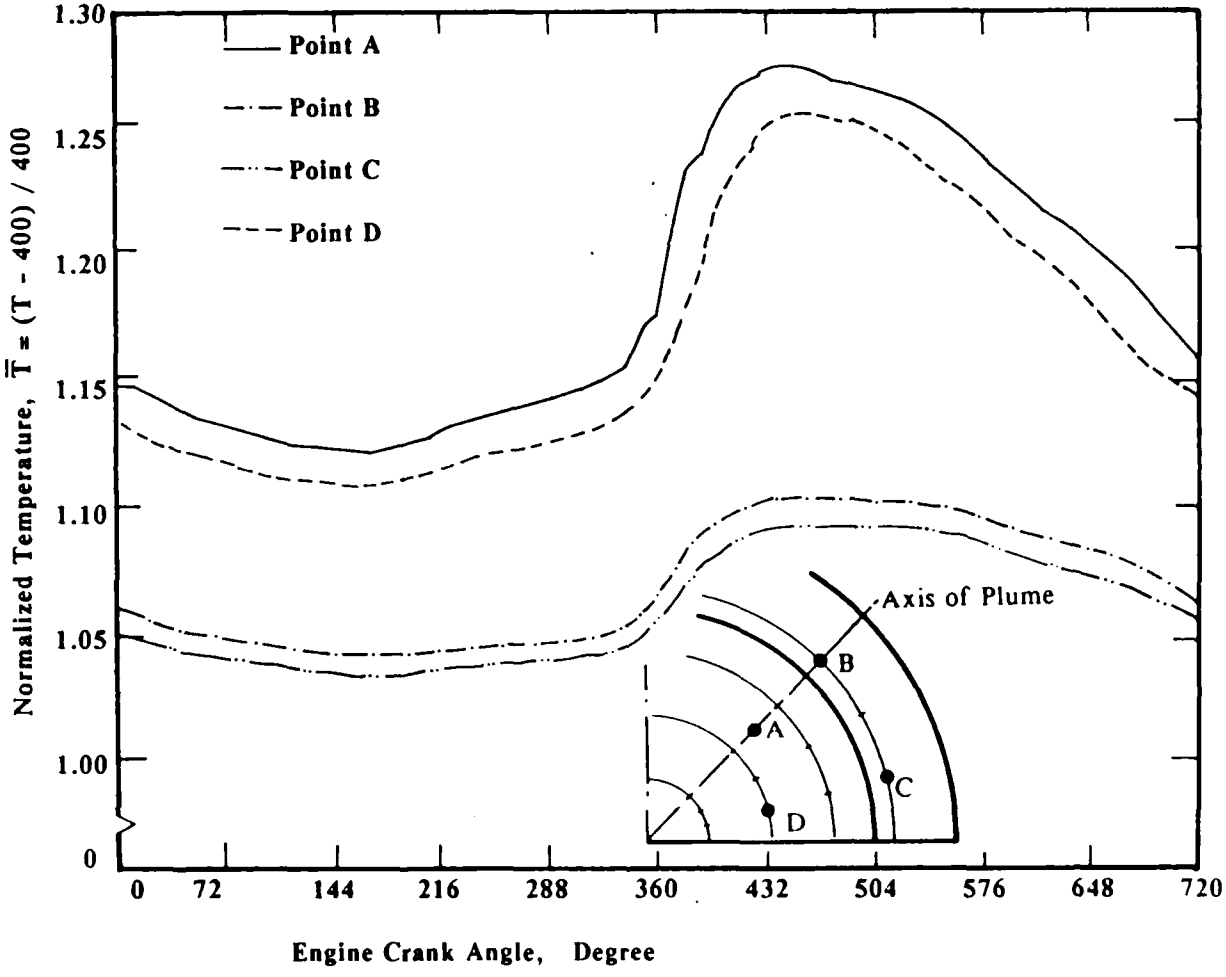


Fig. 10 Instantaneous Temperature at Various Locations over the Piston Top

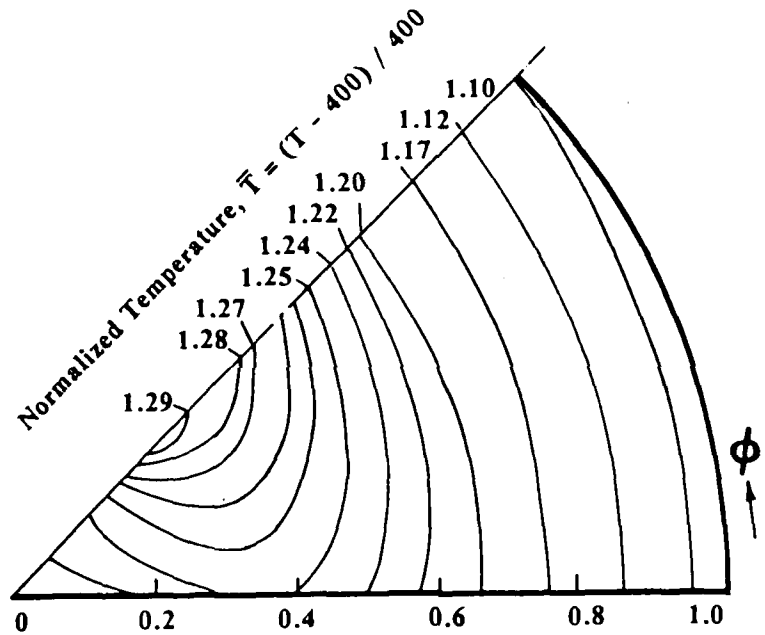


Fig. 11 Instantaneous Temperature Distribution over the Piston Top Surface at Engine Crank Angle of 400.

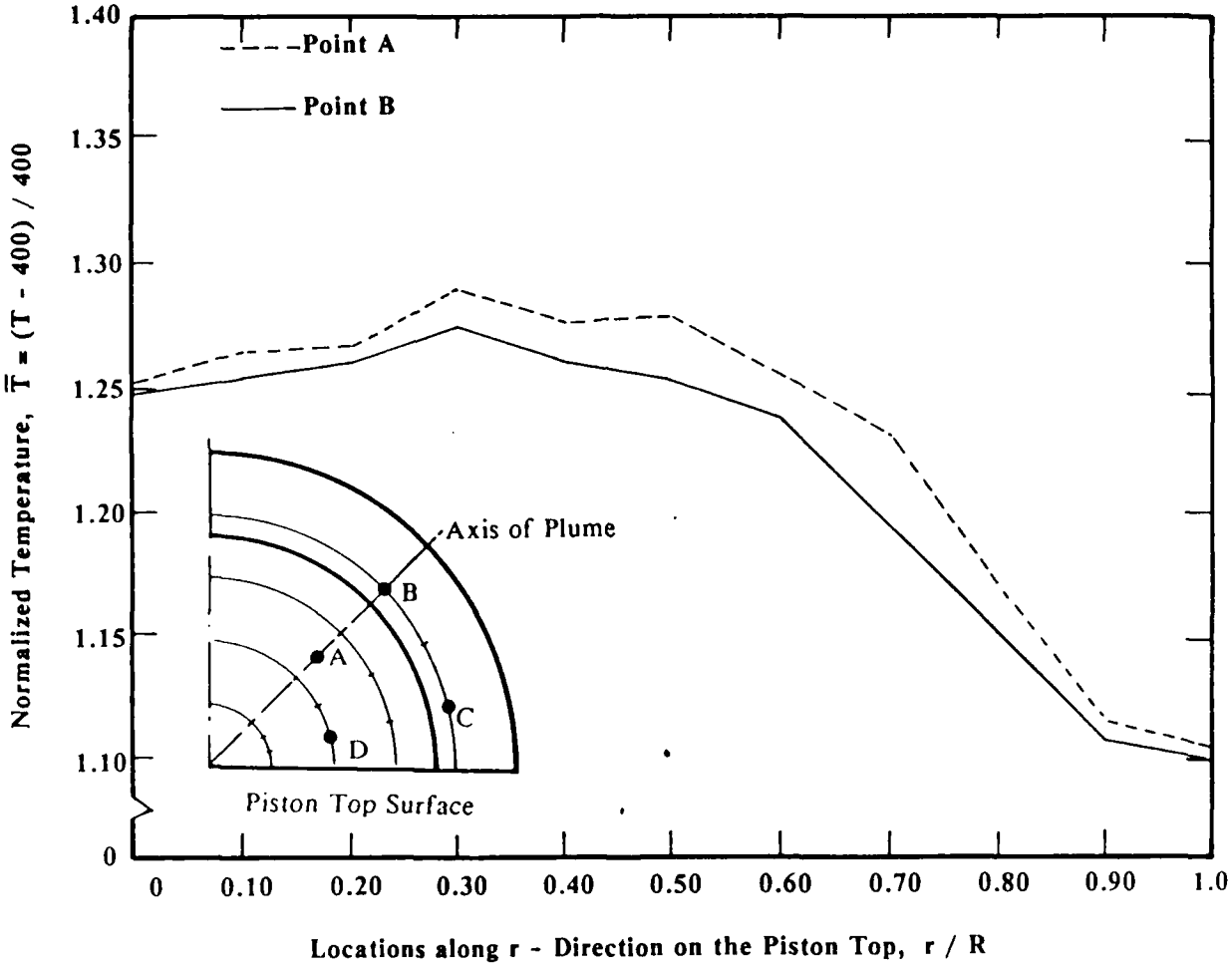


Fig. 12 Temperature Variation along r - Direction on the Piston Top at Engine Crank Angle of 400.

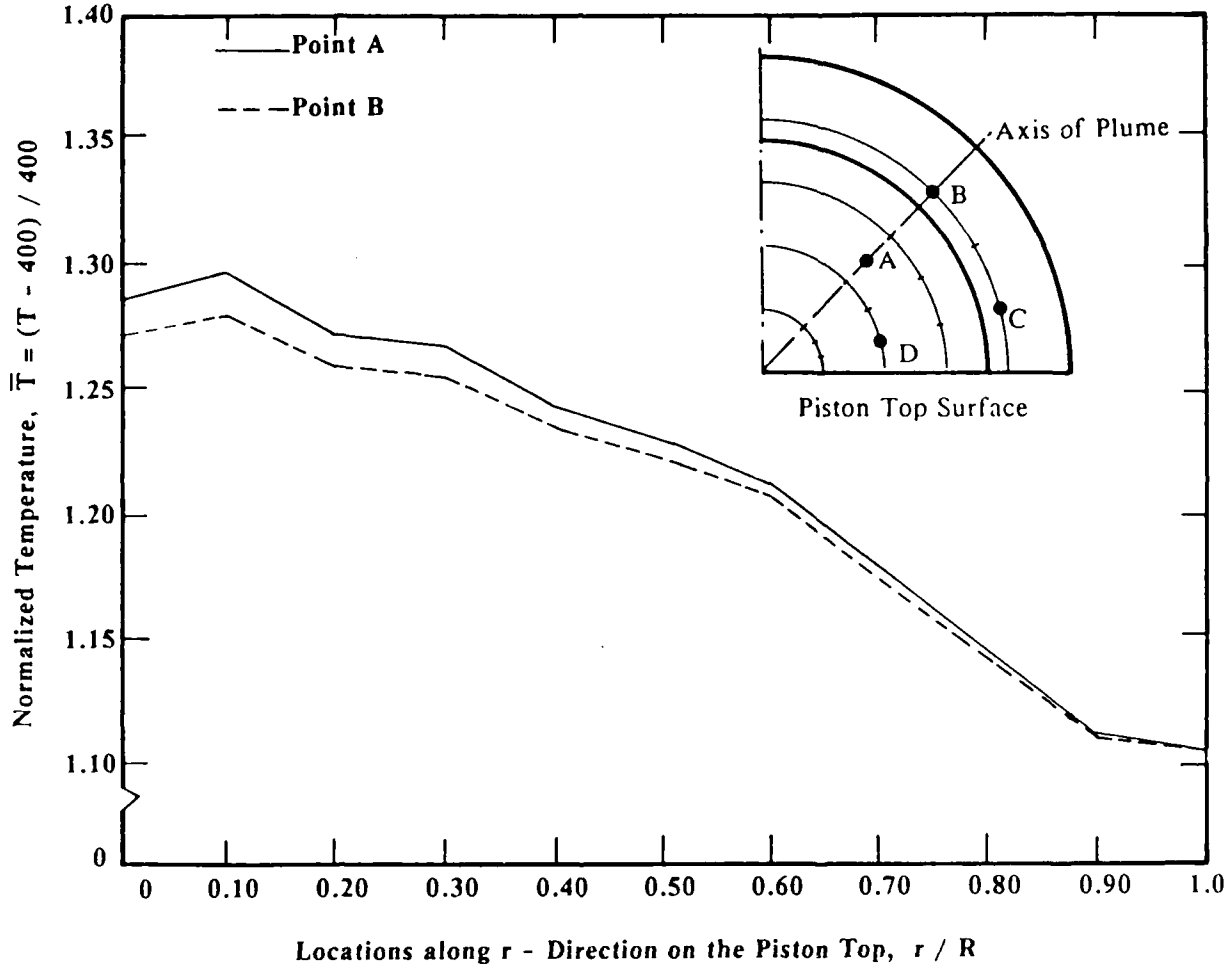


Fig. 13 Temperature Variation along r - Direction on the Piston Top at Engine Crank Angle of 400.

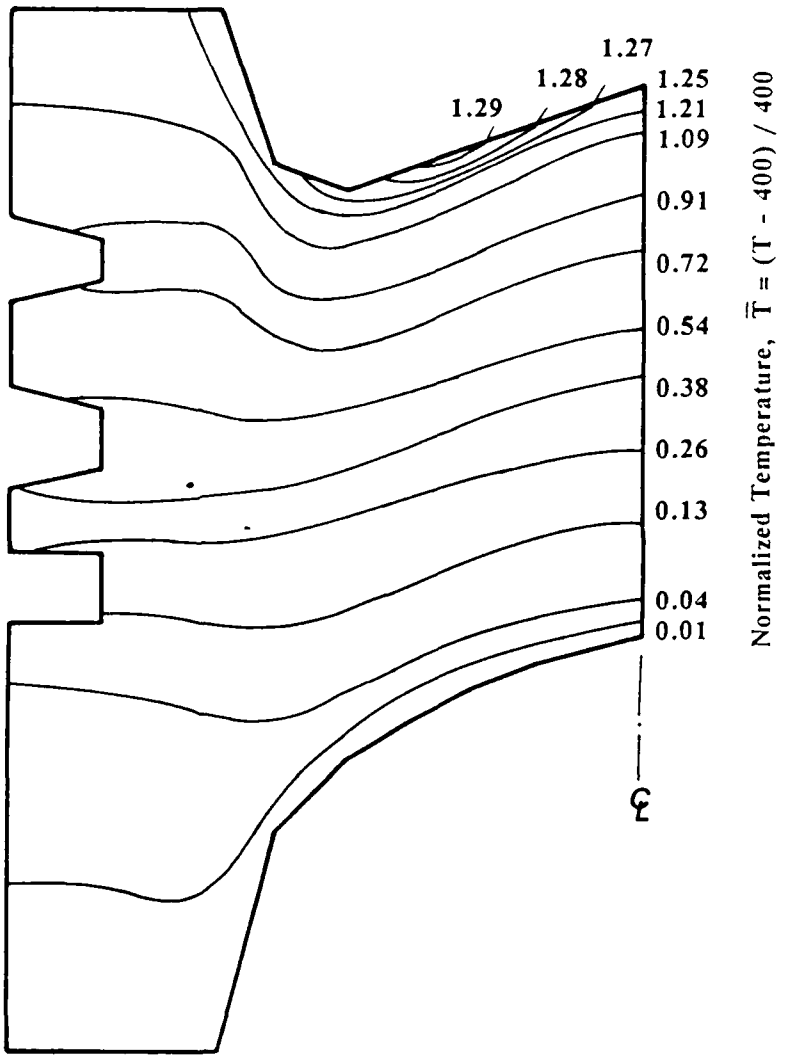


Fig. 14 Temperature Distribution in r - z Plane of a Piston at Engine Crank Angle of 400.

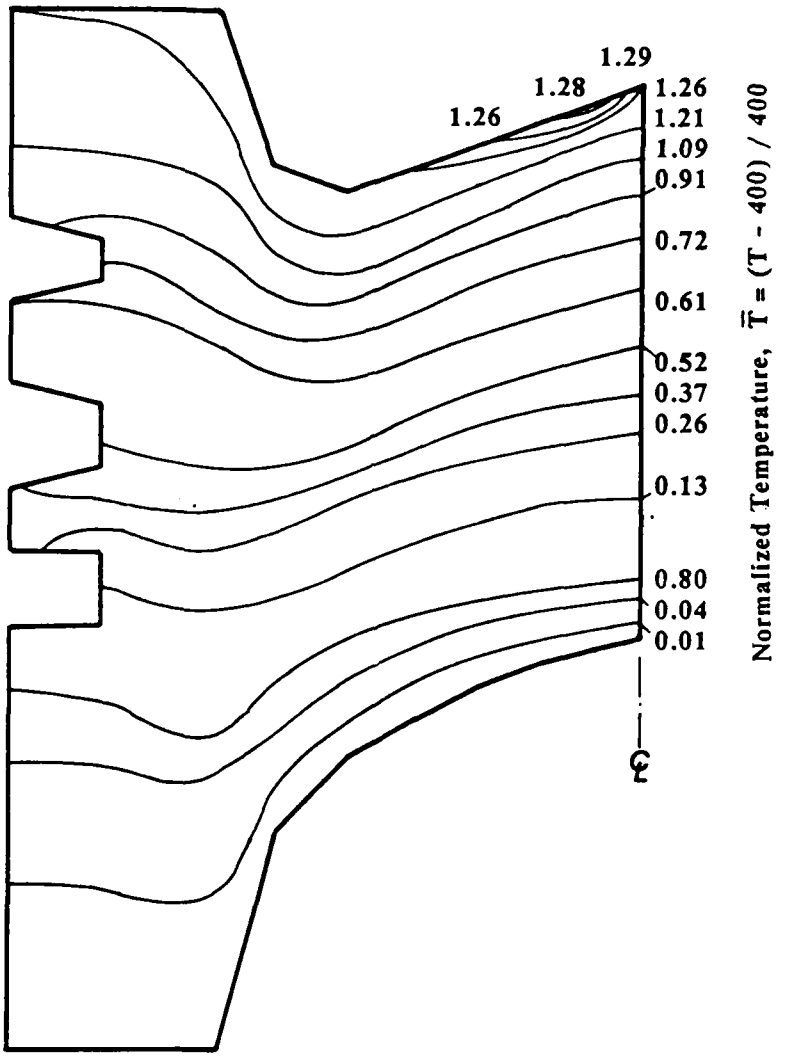


Fig. 15 Temperature Distribution in r - z Plane of a Piston at Engine Crank Angle of 400.

COORDINATE TRANSFORMATION METHOD FOR RADIATION HEAT TRANSFER PREDICTION IN SOOT LADEN COMBUSTION PRODUCTS

by

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INTRODUCTION

Computational modeling of radiative heat transfer has recently become a more important means for the analysis of thermal loading of combustion chambers with luminous flames. This seems to arise due to both the renewed recognition of need for an extensive radiation heat transfer analysis to achieve a better design of many practical systems (e.g., furnace, turbine combustor and diesel engines) and promising new contributions from recent studies enabling more comprehensive modeling. In the modeling, however, several difficult problems are faced, mainly due to the directionality and spectral nature of radiative processes. Most serious problems to be solved in improving its modeling may be listed as follows:

(1) A viable computation of spectral volume absorptance of a mixture of combustion products;

(2) A more accurate computational method for integrating the equation of radiation heat transfer along individual optical paths in the hemispherical volume faced by each location of the reactor wall (hereafter called a detector) and over the wave length range of thermal radiation; and

(3) A detailed description of in-reactor distributions of combustion products and temperature in terms of a suitable coordinate system centered at an individual detector and its coupling with the above radiative transfer equation.

In the present paper, being mainly concerned with the last item of the list, a brief discussion is given for others in order to review the overall problem.

SPECTRAL VOLUME ABSORPTANCE OF SOOT/GAS MIXTURE

When the spectral volume absorptance of combustion products are calculated for the range of thermal radiation, the respective absorptances due to soot cloud and gas mixture are computed as well as their summation. The most widely accepted method of computing the absorptance of soot $\kappa_{\lambda.s}$, by using either Rayleigh limit expression [1] for median size of particles smaller than 0.1 micrometer, or Mie theory [2] for particles with greater sizes where it is required to know the size distribution to take into account scattering. Since practical combustion systems, in general, produce small-size soots, the Rayleigh expression is only considered here. The expression is independent of the size of the particles, inversely proportional to the wavelength λ, and proportional to the soot volume fraction, i.e.,

$$\kappa_\lambda = \frac{36\, n^2\, k(\pi/\lambda)\, f_v}{[n^2(1-k^2) + 2]^2 + 4\, n^4 k^2} \quad . \tag{1}$$

The optical constants, n, k, the real and imaginary parts of the refractive indices, were measured from the intensity of polarizing light reflected from the soot particles and the measurements were fitted to the dispersion equation [3,4]. It was reported that $\kappa_{\lambda.s}$ may slightly increase with wavelength and insignificantly varies with kind of soot and temperature. For computation of emissions from gaseous mixtures, the empirical wide band model proposed by Edwards and Balarkrishnan [5] has often been used [6-8]. The significance of the method is to find, instead of finding gray body absorptance of gas volumes,

the width of individual emission bands, A_λ, compared to blackbody spectrum to approximate the strength of original emission spectrum. This unique technique facilitates an evaluation of the spectral dependence of gas radiation. When emission bands overlap each other at a single spectrum, a separate correction is given [5]. With regard to the summation of both emissions due to soots and gases, even though any method has not fully been verified, several techniques have been used in the past: for an assumed homogeneous and gray body emission, by adding the gas emittance times the soot transmittance to soot emittance [9]; by adding the soot and gas emittances ε_s and ε_g, to find total emittance, ε_t, i.e., $\varepsilon_t = 1-(1-\varepsilon_g)(1-\varepsilon_s)$ [10]; by introducing a new approximation using a pentagamma functional form [11], etc. Unlike those for computation of gray body emittance of gas/soot mixture volume, the summation of spectral emissivity of such mixtures needs special consideration in order to evaluate the spectral dependence of radiation heat transfer. A new method of summing spectral volume absorptances has been used by the authors to find the spectral emittance of combustion products comprising both soot and gases for their recent studies [12]. In the computation of the spectral volume absorptance of a soot/gas mixture, the spectral volume absorptance of gaseous mixture, $\kappa_{\lambda.g}$ is expressed, for convenience of computation, in a form

$$\kappa_{\lambda.g} = C/\lambda \ . \tag{2}$$

Here, C was found from the relationship, $A_\lambda = \int_{\Delta\lambda} 1-\mathrm{Exp}(-C\ell/\lambda)d\lambda$ upon the computation of A_λ for each emission band by using the Edwards' wide band non-gray model. On the other hand, the volume absorptance due to soot suspending in the mixture, $\kappa_{\lambda.s}$, (Eq. 1) is used to find C' from the expression $\kappa_{\lambda.s} = C'/\lambda$. The spectral absorptance of soot/gas mixture, κ_λ, is then computed from the following:

$$\kappa_\lambda = (C+C')/\lambda \tag{3}$$

This method for quantifying spectral dependence of radiative processes of a combustion gas mixture with soot suspension is basically similar to one of those listed above for gray body radiation analysis. That is, a summation for individual spectral emissivity of such mixtures by using the new method, without exceeding blackbody emissivity at a spectrum upon the addition of both emissions, is quite equivalent to the following relationship:

$$\varepsilon_{t.\lambda} = 1-(1-\varepsilon_{g.\lambda})(1-\varepsilon_{s.\lambda}) \tag{4}$$

The validity of the new summation method, however similar to one often employed for gray body analysis, is not fully accepted at present, so that a future systematic experimental evaluation of summation is needed. Further, since the calculation of emittance as a thermal equilibrium mixture is made by computing the spectral volume absorptance instead of emittance as explained above, the assumption of Kirchhoff's law to hold for it in a system is more justified than a similar assumption made for gray body computations.

EQUATION OF RADIATION HEAT TRANSFER EQUATION

The equation of radiation heat transfer in radiatively participating fluids confined in a volume is well known. The governing equation of monochromatic radiation heat transfer is sought for the processes in combustors containing plumes of small size soot laden flames as shown in Fig. 1 where pertinent details are shown, e.g., geometric information and spectral reflectivity of wall surfaces, $\beta_{I\lambda}$, etc. Referring to Fig. 1, the governing equation of local spectral radiation intensity, $I_\lambda(r)$, is written as

$$I_\lambda(r) = \int_r^{r_o} \frac{\kappa_\lambda(r')}{\pi} e_{b\lambda}(r') \, \mathrm{Exp}\left(-\int_r^{r'} \kappa_\lambda(r'')dr''\right)dr' \, , \tag{5}$$

where, $e_{b\lambda} = \frac{2\pi hc^2}{\lambda^5 [Exp(hc/\lambda KT)-1]}$, κ_λ is the spectral volume absorptance at (r,θ,ζ), $c = 2.998 \times 10^{10}$ cm/sec, $h = 6.625 \times 10^{-27}$ erg-sec, and $k = 1.380 \times 10^{-16}$ erg/K. The heat flux along an optical path of a solid angle (θ,ζ) in the thermal radiation range may be, then, computed from

$$q_{\theta\zeta} = \int_0^\infty I_\lambda(0) \cos\theta \, d\lambda \tag{6}$$

The main difficulty in finding the solution of Eq. (5) resides in the fact that κ_λ is a function of both species concentrations and temperature and that both variables are a function of the location along the individual optical path, r. The present paper considers a new technique to describe the species distribution along individual optical paths and its coupling with Eq. (5). When such distribution details become available, a more realistic solution of Eq. (6) is accessible, as reported elsewhere [13].

The surface properties are combined with the radiation heat fluxes incident on individual locations of the combustor wall. The extinction coefficient, $\tau_\lambda = \int \kappa_\lambda \cdot dL$, along each optical path found from the computation as explained above and the spectral reflectivities, $\beta_{\lambda\cdot 1}$, are included in the expression for the radiosity of surface 1, $B_{\lambda 1}$, as

$$B_{\lambda 1} = \frac{(I_1 + \beta_{\lambda 1} \cos\theta_1 \, I_\lambda(0)) + \beta_{\lambda 1} \cos\theta_1 \, e^{-\tau_\lambda} \, (I_2 + \beta_{\lambda 2} \cos\theta_2 \, I_\lambda(0))}{1 - \beta_{\lambda 1} \beta_{\lambda 2} \cos\theta_1 \cos\theta_2 \, e^{-2\tau_\lambda}} \tag{7}$$

Upon implementation of computations by coupling Eq. (5) with Eq. (7), the net heat transferred through a chosen spectrum at a detector can be calculated.

IN-COMBUSTOR SPECIES DISTRIBUTION

Since an analysis of space- and spectrum-resolved radiation heat transfer in a combustor, as considered here, requires detailed distributions of in-reactor species and temperature, search of a useful technique for this is clearly warranted. Unfortunately, at present neither convenient means for obtaining in-combustor data sufficient for use in radiation heat transfer analysis has been available. The distributions may be obtained by either experimental or theoretical method. Some activity is underway in the direction of obtaining such information in the authors' laboratory. When the distribution becomes available, it is most convenient to express it in a coordinate system centered at the fuel injection nozzle.

Although, as explained above, the species distribution in plumes of combustors equipped with the fuel injection nozzle is not readily available, a new approach explained in the following may shed light in the search for a viable solution to the problem. It is found from some experimental and theoretical results in literature that the species distribution in non-axisymmetric plume of such systems [14,15] may conveniently be described by the following equation in a cylindrical coordinate:

$$F = F_o \exp(-a\rho - b\phi^2 - cz^2) \tag{8}$$

where F may represent either fuel/air ratio, or soot concentration, or CO_2 or H_2O concentrations; F_o, a, b and c are constants to be separately determined by either experimental or theoretical means for individual combustion units. This expression of plumes, however, deemed rather simple and probably less realistic, is considered to serve a suitable method for some parametric analysis of the confronting problem. Among the advantages of this approach is that the deformation of plume, e.g. in spiral direction, due to swirl motion while the fuel spray is

formed, may be reasonably described for both transient and steady combustion systems, i.e, by including it in ϕ-direction, as explained later.

The next task to be implemented for the final solution may be a proper coupling of, with Eq.(5), the details of in-combustor species distribution that may be obtained from the above method or others. Several techniques have been employed in finding a solution of the equation of radiation heat transfer (Eq. (5), namely, the Monte-Carlo method [10,16], the zonal method [17,18], the use of geometric factors [6,19], etc. Those methods did not rigorously implement the solution of Eq. (5), but sought for approximated solution and gray-body computation. Among the main reasons for this is that it is difficult to find species distribution along individual directions of integration in the hemispherical volume faced by the location where heat transfer is considered. The difficulty is compounded when the distribution varies with time as in transient-flow combustors.

COORDINATE TRANSFORMATION

In view of the discussion above on the overall problem in finding space- and spectral-resolved radiation heat transfer in combustors, it is highly desirable to find a more versatile method enabling us to find a better solution of Eq. (5). A new technique for the goal is presented in the following. The basic idea of the technique is to employ coordinate transformations for finding the species distribution along the individual optical direction, r, (Fig. 1) in an equational form by using the species distribution given in a coordinate with respect to the fuel injector. When such an equation in a suitable coordinate centered at detectors on the combustor wall becomes available, i.e. along individual optical direction with respect to the detector, a better computation of the space-resolved radiation heat transfer can be attempted.

As explained earlier, it was found to be convenient to express, in a cylindrical coordinate, the spray plumes of which geometry and others vary with time. The following discussion is concerned with description of the same plumes in a new coordinate system with respect to a detector of interest, consequently to make available the species distribution along individual optical paths centered at the detector. This goal is achieved by using a new coordinate transformation technique involving two main sets of coordinate systems, i.e., a cylindrical coordinate centered at the injection nozzle hole, O, for describing the spray plumes (ρ,ϕ,z) and a spherical coordinate (r,θ,ζ) for expressing the same plumes with respect to the detector located at D. Two transformation techniques are presented: (1) point-to-point transformation; and (2) distribution equation-to-distribution equation transformation. The former is considered to be particularly useful when some discrete point data are available in a coordinate with respect to the injection nozzle for expressing them in a new coordinate centered at a detector. The latter is developed for transforming a functional expression of the spray plume in a nozzle coordinate, e.g. Eq. (8), to find an equational spray description in a new detector coordinate.

(1) Point-to-point Transformations

MUTUALLY PARALLEL COORDINATES - When in-combustor species data is experimentally acquired [20], it is always likely that they become available in a set of discrete data points as opposed to in a form of continuous variation in species concentration of plumes. When one uses such discrete data points in computing radiation characteristics in a direction of optical path with respect to a detector, it is necessary to know a species distribution along individual optical paths for solving Eq. (5). For such needs, a new approach of using point-to-point coordinate transformation is introduced. To perform a coordinate transformation between these systems, two more intermediate coordinate systems,

X and Y, are introduced for the convenience of derivation. The axes of the coordinates under consideration are either parallel or perpendicular to each other in order to avoid the complexity of the derivation although cases with the mutually non-parallel coordinates are discussed later. The interim coordinate systems are listed in the following and shown in Fig. 2-(A).

a. Spray plume coordinate (cylindrical), C (ρ,ϕ,z)

b. X coordinate, X (x_1,x_2,x_3)

c. Y coordinate, Y (y_1,y_2,y_3)

d. Detection coordinate (spherical) S (r,θ,ζ)

Identifying the location of a detector at x_{1d}, x_{2d}, x_{3d}, a series of transformations are carried out to obtain

$$\rho^2 = r^2 \sin^2\theta + 2 r \rho_d \sin\theta \cos(\phi_d+\zeta) + \rho_d^2,$$

$$\phi = \tan^{-1}[(\rho_d \sin\phi_d - r \sin\theta \sin\zeta)/(\rho_d \cos\phi_d + r \sin\theta \cos\zeta)],$$

$$Z = Z_d - r \cos\theta , \qquad (9)$$

where, $\rho_d^2 = x_1^2 + x_2^2$, $\phi_d = \tan^{-1}(x_2/x_1)$, and $z_d = x_3$. Note that $\phi = \tan^{-1}(x_2/x_1)$ if $x_1 \geq 0$, $\phi = \tan^{-1}(x_2/x_1) + \pi$ if $x_1 < 0$ and $x_2 > 0$ and $\phi = \tan^{-1}(x_2/x_1) - \pi$ if $x_1 < 0$ and $x_2 < 0$.

MUTUALLY UNPARALLEL COORDINATES - However, since in many practical systems, e.g., diesel engines, the fuel is injected into the combustion chamber at an angle, θ_{in}, as shown in Figs. 1 and 2-(B), this has to be taken into consideration in the coordination transformation. In order to meet this need, an additional coordinate system having an angle of θ_{in} with respect to the cylinder coordinate (x_1,x_2,x_3) is introduced. The new coordinate (u_1,u_2,u_3) is not parallel to the detector coordinate (y_1,y_2,y_3). Their mutual relationship may be listed as follows:

$$x_1 = \rho \cos\phi,\ x_2 = \rho \sin\phi,\ x_3 = Z\ ;$$

$$u_1 = x_1 \cos\theta_{in} - x_3 \sin\theta_{in}\ ;$$

$$u_2 = x_2\ ;$$

$$u_3 = x_1 \sin\theta_{in} + x_3 \cos\theta_{in}\ ;$$

$$\rho_u^2 = u_1^2 + u_2^2\ ;$$

$$\theta_u = \tan^{-1}(u_2/u_1)\ ;\ \text{and}$$

$$z_u = u_3\ .$$

Further, an expression similar to Eq. (9) can be obtained as

$$\rho_u^2 = (\rho \cos\theta_{in} \cos\phi - z \sin\theta_{in})^2 + \rho^2 \sin^2\phi$$

$$\phi_u = \tan^{-1}[(\rho \sin\phi)/(\rho \cos\theta_{in} \cos\phi - z \sin\theta_{in})]$$

$$z_u = \rho \sin\theta_{in} \cos\phi + z \cos\theta_{in}\ .$$

Accordingly, the location of detector, initially identified by using the parallel coordinate (ρ,θ,z) can finally be rewritten in terms of the unparallel system (ρ_u,r_u,z_u) (see Fig. 2-(B) as,

$$\rho_u^2 = (\rho_d \cos\theta_{in} \cos\phi_d - z_d \sin\theta_{in})^2 + \rho_d^2 \sin^2\phi_d\ ,$$

$$\phi_u = \tan^{-1}[(\rho_d \sin\phi_d)/(\rho_d \cos\theta_{in} \cos\phi_d - z_d \sin\theta_{in})]\ \text{and}$$

$$z_u = \rho_d \sin\theta_{in} \cos\phi_d + z_d \cos\theta_{in}\ . \qquad (10)$$

Since it is readily found that the geometric configurations of the inclined plume vs. the coordinate (y_1,y_2,y_3) is equivalent to those of the similar plume with axis in x_1 vs. an equally inclined detector coordinate (u_1',u_2',u_3'), some pertinent conversion may be made. Converting the geometric details of a given solid angle initially represented by using (θ,ζ) into an expression in terms of corresponding unparallel coordinate (θ_u,ζ_u), the results obtained for the case of mutually parallel coordinate, Eq. (9), can directly be used. For this, the conversion for the solid angle is achieved by

$$\theta_u = \cos^{-1}[-\sin\theta \cos\zeta \sin\theta_{in} + \cos\theta \cos\theta_{in}]$$

$$\zeta_u = \tan^{-1}[\sin\theta \sin\zeta/(\sin\theta \cos\zeta \cos\theta_{in} + \cos\theta \sin\theta_{in})] \qquad (11)$$

The location of a data point originally identified in terms of the coordinate of plume of which axis is inclined by an angle of θ_{in} with respect to a perpendicular coordinate can, therefore, be expressed in terms of a spherical coordinate centered at a detector on the combustor wall by introducing Eqs. (9) and (10) into Eq. (11).

(2) Distribution-to-Distribution Transformations

WITHOUT SWIRL MOTION - As explained earlier, the details of in-combustor spray plume may be obtained in an equational form, e.g. Eq. (8), expressed with respect to the nozzle hole. The transformation of such distribution to individual distributions along an individual optical path at a detector is considered for a combustor without swirl motion. The logical step for this goal would have been introducing the corresponding terms of Eq. (9) into Eq. (8). Such transformation, however, results in an extremely complex form of Eq. (8) expressed in terms of the spherical coordinate at the detector. Furthermore, the new transformed distribution equation becomes too difficult to be used in Eq. (5). In order to alleviate the problem, an approximation technique was sought in such a way as to conveniently use its results in obtaining the solution of Eq. (5). It was found that use of the Taylor expansion method in the transformation not only greatly facilities the steps toward the final goal but also lead to very accurate results.

ρ-terms:

Letting $\chi \equiv r \sin\theta/\rho_d$, $A \equiv \cos(\phi_d + \zeta)$, with $f \equiv \rho/\rho_d$, one finds

$$f(\chi) = (1 + 2A\chi + \chi^2)^{1/2},$$

$$f'(\chi) = (A+\chi)/f \text{ , and}$$

$$f''(\chi) = [f^2(\chi) - (A+\chi)^2]/f^3$$

For $\chi = \chi_i + \varepsilon$ and $\varepsilon << 1$ the above may be rewritten as,

$$f(\chi) \cong f(\chi_i) + f'(\chi_i)\,\varepsilon + f''(\chi_i)\varepsilon^2/2$$

Further, since $\varepsilon = \chi - \chi_i$, $f(\chi)$ may be expressed as

$$f(\chi) = \rho/\rho_d \cong f_0 + f_1 + f_2\,\chi^2 \qquad (12)$$

where, $f_0 = f(\chi_i) - f'(\chi_i)\,\chi_i + f''(\chi_i)\,\chi_i^2/2$,

$f_1 = f'(\chi_i) - f''(\chi_i)\,\chi_i$, and

$f_2 = f''(\chi_i)/2$.

For $\chi >> 1$, $f(\chi) = \rho/\rho_d \cong \chi + A$

φ terms:

From Eq. (9), having $f(\chi) = \tan(\phi)$

$$= (\sin\phi_d - \chi \sin\zeta)/(\cos\phi_d + \chi \cos\zeta),$$

one obtains

$$f'(\chi) = -\sin(\phi_d + \zeta)/(\cos\phi_d + \chi\cos\zeta)^2,$$

$$f''(\chi) = -2\, f'(\chi)\cos\zeta/(\cos\phi_d + \chi\cos\zeta),$$

$$\phi(\chi) = \tan^{-1}(f)$$

$$\phi'(\chi) = f'/(1+f^2), \text{ and}$$

$$\phi''(\chi) = [-2\, ff'^2 + (1+f^2)\, f'']/(1+f^2)^2.$$

Note, for $\cos\phi_d + \chi\cos\zeta = 0$, $\phi(\chi) = \pi/2$, $\phi'(\chi) = -\cos^2\zeta/\sin(\phi_d+\zeta)$ and $\phi''(\chi) = 0$. For $\chi = \chi_i+\varepsilon$ and $\varepsilon \ll 1$, $\phi(\chi)$ may be written as $\phi(\chi) \cong \phi(\chi_i) + \phi'(\chi_i)\,\varepsilon + \phi''(\chi_i)\,\varepsilon^2/2$.

In view of Eq. (8), one defines $\Phi(\chi) = \phi^2(\chi)$ to rewrite

$$\Phi(\chi) \cong \Phi(\chi_i) + \Phi'(\chi_i)\,\varepsilon + \Phi''(\chi_i)\,\varepsilon^2/2$$

where $\Phi'(\chi) = 2\phi(\chi_i)\,\phi'(\chi_i)$

$$\Phi''(\chi) = 2\phi(\chi_i)\,\phi''(\chi_i) + 2\phi'^2(\chi_i)$$

Further, since $\varepsilon = \chi-\chi_i$, Φ may be expressed

$$\Phi(\chi) \cong \Phi_o + \Phi_i\,\chi + \Phi_2\,\chi^2 \qquad (13)$$

where, $\Phi_0 = \Phi(\chi_i) - \Phi'(\chi_i)\,\chi_i + \Phi''(\chi_i)\,\chi_i^2/2$

$$\Phi_1 = \Phi(\chi_i) - \Phi''(\chi_i)\,\chi_i$$

$$\Phi_2 = \Phi''(\chi_i)/2$$

For $\chi \gg 1$, $\phi(\chi) \cong -\zeta$, or $\Phi(\chi) \cong \zeta^2$.

z-terms:

Since z is a single first order polynomial function of r, the following is obtained from Eq. (9).

$$z^2 = z_d^2 - 2\, z_d\, r \cos\theta + r^2 \cos^2\theta \qquad (14)$$

Finally, by substituting terms in Eq. (8) with Eqs. (12), (13) and (14), one obtains

$$F = f_d\, e^{-[(r-r_o)/r_w]^2} \qquad (15)$$

where, $f_d = f_o\, e^{-(a_1 - b_1^2/4C_1)}$,

$r_o = b_1/2\, C_1$,

$r_w = (C_1)^{-1/2}$,

$a_1 = a\, \rho_o + b\, \Phi_o + C\, z_d^2$,

$b_1 = -[a\, \rho_1 + b\, \Phi_1]\, \sin\theta/\rho_d + 2\, Cz_d \cos\theta$, and

$c_1 = [a\, \rho_2 + b\, \Phi_2]\, \sin^2\theta/\rho_d^2 + C\cdot\cos^2\theta$.

When the above results are used in solving Eq. (5), it is found that the above approximation method generates better accuracy when the integral interval is divided into smaller subranges.

WITH SWIRL MOTION - The present coordinate transformation method is also considered for a combustor with swirl motion. With swirl motion, prior to the transformation, the spray plume distribution equation, Eq. (8), needs adjustments to take into account the bending of spray plume. Although the exact formation mechanism of bent sprays in the presence of gas swirl in the combustor is not properly understood at present, the following two probable cases are considered.

Droplet with Constant Axial Velocity:

It is assumed that (1) fuel droplets ejected from the nozzle hole to move at a constant axial velocity, v_f; (2) the angular velocity of the swirl, Ω, is constant along the axis of the plume; (3) the angular velocity of fuel droplets along the plume axis is the same as Ω. With the above, a point characteristic at a location (ρ,ϕ,Z) of no-swirl condition is found at a location $(\rho,\phi+\phi_s,Z)$, due to the swirl during a period of time Δt, according to

$$\phi_s = (\Omega/v_f)\rho,$$
$$\phi_s' = \Omega/v_f \text{ and}$$
$$\phi_s'' = 0.$$

In this case Eq. (8) becomes $F = F_o \exp[-a\rho - b(\phi-\phi_s)^2 - Cz^2]$. The transformation of the above equation into the detector coordinate expression is exactly identical except for a new set of equations in ϕ-terms. They are:

$$\Phi(x_i) = \psi^2(x_i),$$
$$\Phi'(x_i) = 2\psi(x_i)\,\psi'(x_i), \text{ and}$$
$$\Phi''(x_i) = 2\psi(x_i)\psi''(x_i) + 2\psi'^2(x_i), \qquad (16)$$

where, $\psi(x_i) = \phi(x_i) - \phi_s(x_i)$,
$\psi'(x_i) = \phi'(x_i) - \phi_s'(x_i)$ and
$\psi''(x_i) = \phi''(x_i) - \phi_s''(x_i)$.

Droplets with Specified Axial Velocity:

Melton [21] analyzed a case for the plume formation as

$$v_f = v_s/(1+\alpha\rho)$$

where, v_s is the exit velocity of the fuel droplet at the nozzle hole, α is about 0.085/Rs and Rs is the radius of the nozzle hole. Assumptions of the previous case are also similarly taken here for finding $\phi_s = \Omega \cdot t$, since $v_f = d\rho/dt = v_s/(1+\alpha\rho)$ and $\rho + \alpha\rho^2/2 = v_s\, t$.

Combining the above, one finds

$$\phi_s = (\Omega\rho/v_s)\ (1+\alpha\rho/2).$$

Letting $\phi_{s1} \equiv (\Omega/v_s)\ (1+\alpha/2)$, the above equation may be expressed in terms of ϕ_{s1} to obtain

$$\phi_s = \phi_{s1}\ \rho(1+\alpha\rho/2)/(1+\alpha/2),$$

$$\phi_s' = \phi_{s1}(1+\alpha\rho)/(1+\alpha/2) \text{ and}$$

$$\phi_s'' = \phi_{s1}\ \alpha/(1+\alpha/2).$$

Substituting respective terms in Eq. (16) by the above results, the coordinate transformation of bending spray plumes, as specified here, can be achieved.

Regarding the plumes with their axis having an inclined angle of θ_{in}, the distribution-to-distribution transformation can be obtained by introducing Eqs. (11) and (12) into Eq. (15).

COMPUTATION OF RADIATION IN DIESEL COMBUSTION

The present method may readily be used for analysis of radiation heat transfer processes in combustors having jet flames. An analysis may be made over the entire wall of the reactor to introduce the results to implement a global analysis of the system heat transfer including convective and conduction heat transfers, which will enable prediction of the temperature distribution

into and over the wall. When an unsteady combustion reactor is considered, e.g., a diesel engine, the analysis will have to be made over the entire cycle period along with energy conversion process, as presently attempted in our laboratory. The present section, however, considers the computation of radiation heat transfer at a particular engine crank angle. Since more extensive results are reported elsewhere [22], only a few computations are described here. Among the assumptions employed due to the absence of either sufficient engine data or suitable engine modeling are (1) the values of constants in Eq. (8) are F_0 for soot, H_2O, CO_2 and burned fuel/air ratio, 8×10^{-6}, 0.01, 0.01, and 1.0, respectively; the distribution constants, a, b and c are 0.6, 2.36, and 2 for the above cases accordingly. (For example, the CO_2 distribution in the plume may be written as $F = \{0.01\ \text{Exp} - [0.6(\rho/R) + 2.43(\phi/\phi_r) + 2.0(z/R)^2]\}$, where R is the piston radius and ϕ_r is π/(number of plumes), (2) other engine details are, the surface temperature, 500°K; the number of plumes, 4, the piston radius, 4.92 cm; the combustion chamber bowl radius, 3.44 cm, and the fuel composition $C_{16}H_{34}$, (3) the computation of the temperature distribution is computed by using the equilibrium adiabatic temperature relationship to the fuel/air ratio (e.g., using a new method [23]), etc. The computed radiation heat flux is presented presented in terms of the following nondimensionalized terms: the normalized spectral energy, $Q_\lambda/Q_{b\lambda}$, and the normalized directional radiation intensity, $I(\rho,\phi,z)/I_b$, where, $Q_{br} = \sigma T_r^4$, T_r = 2,400°K, $I_b = Q_{br}/\pi$, and σ is the Stefan-Boltzman constant (5.670×10^{-8} W/m^2 K^4).

Shown here are the following case analyses: (1) the spectral radiation heat incident upon locations on the cylinder head along the axis of a spray plume at r = 0.0R, 0.5R and 0.9R (Fig. 3), (2) the normalized directional radiation intensity streaming into the injection nozzle tip (ρ = 0.0, ϕ = 0.0) along the direction of zenith angle in the hemispherical volume faced by the tip (Fig. 4)

and (3) the normalized directional radiation intensity along the locations on the cylinder head right above the axis of the spray plume in directions of zenith angle, θ = 17.6, 60.0 and 76.7 in the hemispherical volume faced by each location (Fig. 5). Without discussing the details of the results, one may readily find from the above illustration that improved radiation heat transfer computations can be achieved by employing the present new coordinate transformation method in its modeling.

ACKNOWLEDGMENT

The present work has been supported by the U.S. Army Research Office, Contract No. DAAG29-83-K-0042 (Scientific Program Officer, Dr. David M. Mann).

NOMENCLATURE

- A band absorptance
- a constant determining species distribution
- B radiosity
- b constant determining species distribution
- c speed of light or constant determining species distribution
- e Plank's emission power
- F species distribution function
- f soot volume fraction or transformation function
- h Plank's constant
- I radiation intensity
- k Boltzman constant or imaginary part of reflective index
- n real part of the reflective index
- Q black body radiation
- q radiation heat flux

R radius of cylinder

T temperature

t time

v velocity

χ component of cartesian coordinate X

y component of cartesian coordinate Y

α constant for plume injection speed

β reflectivity of cylinder wall

γ,θ,ζ components in spherical coordinate, C

ε emittance

θ angle of optical path with respect to normal

κ volume absorptance

λ wavelength

ρ,ϕ,Z components in cylindrical coordinate, S

τ extinction coefficient

Φ transformation function

Ω angular speed

Subscripts

b blackbody

d detector

g gas

in inclined

o constant

s soot

t total

u unparallel

λ spectral

θs optical path of solid angle

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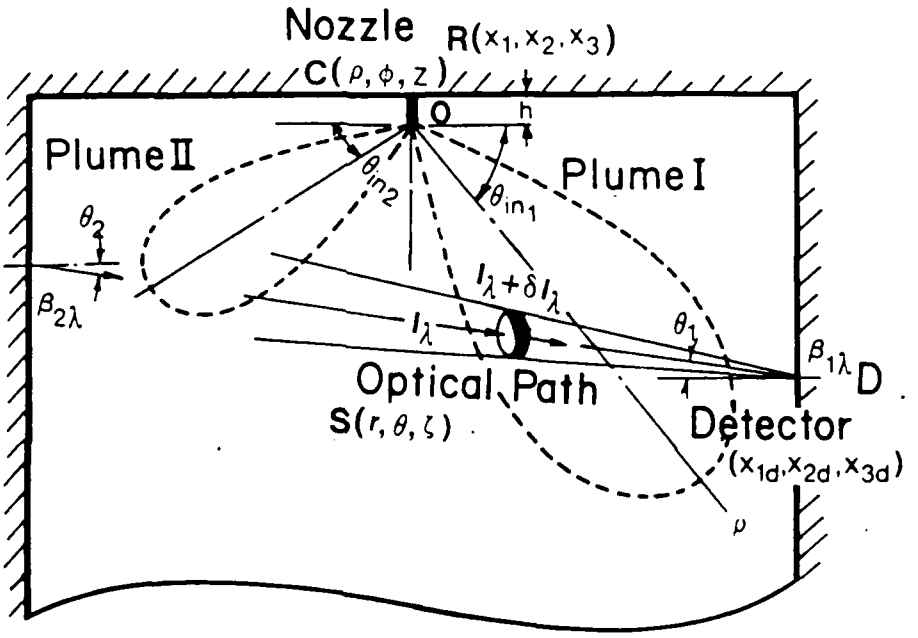


Fig. 1. Soot laden flames in a combustion chamber

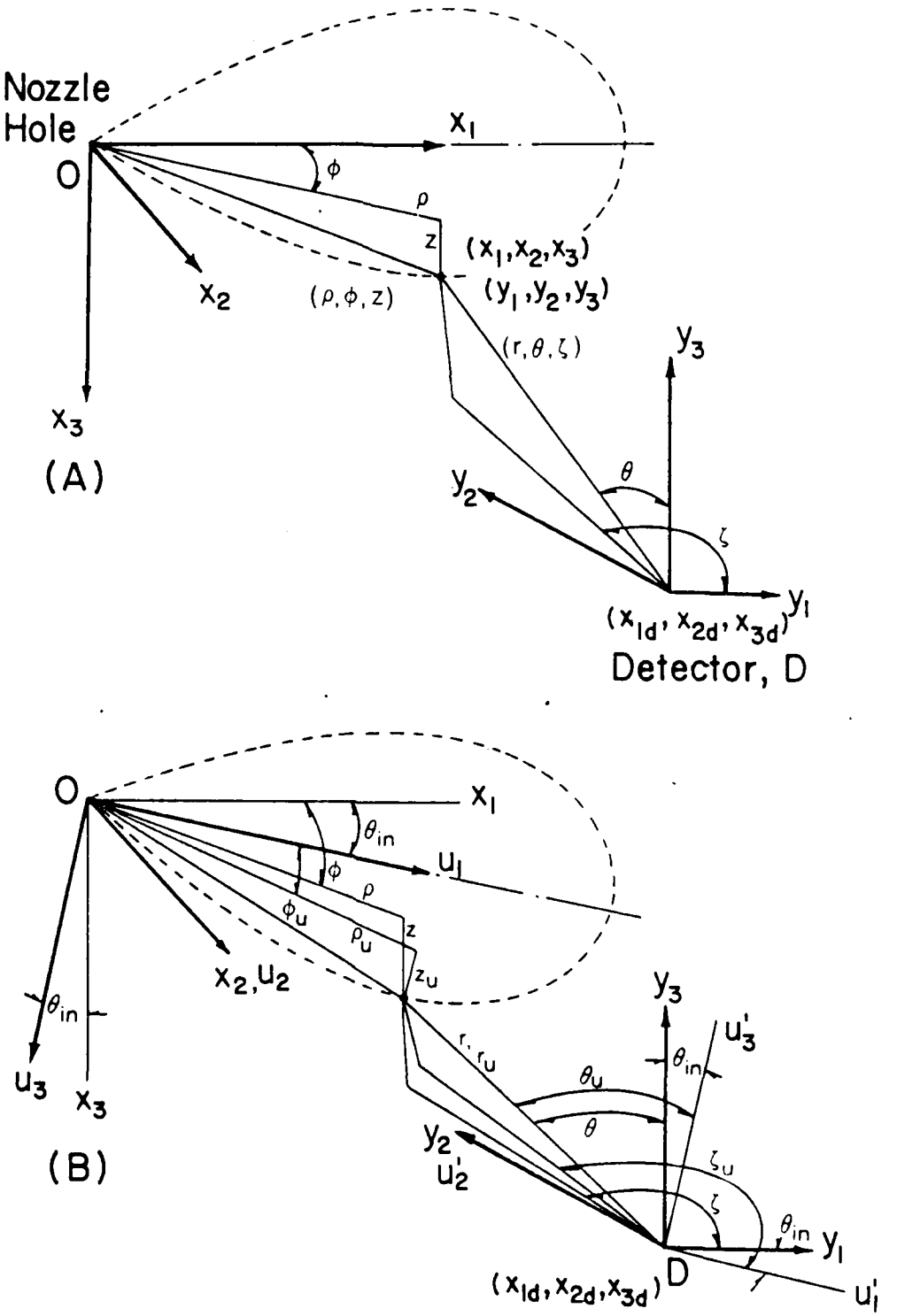


Fig. 2. Detector location with respect to flame plume.
(A) Parallel Coordinate and (B) Unparallel Coordinate

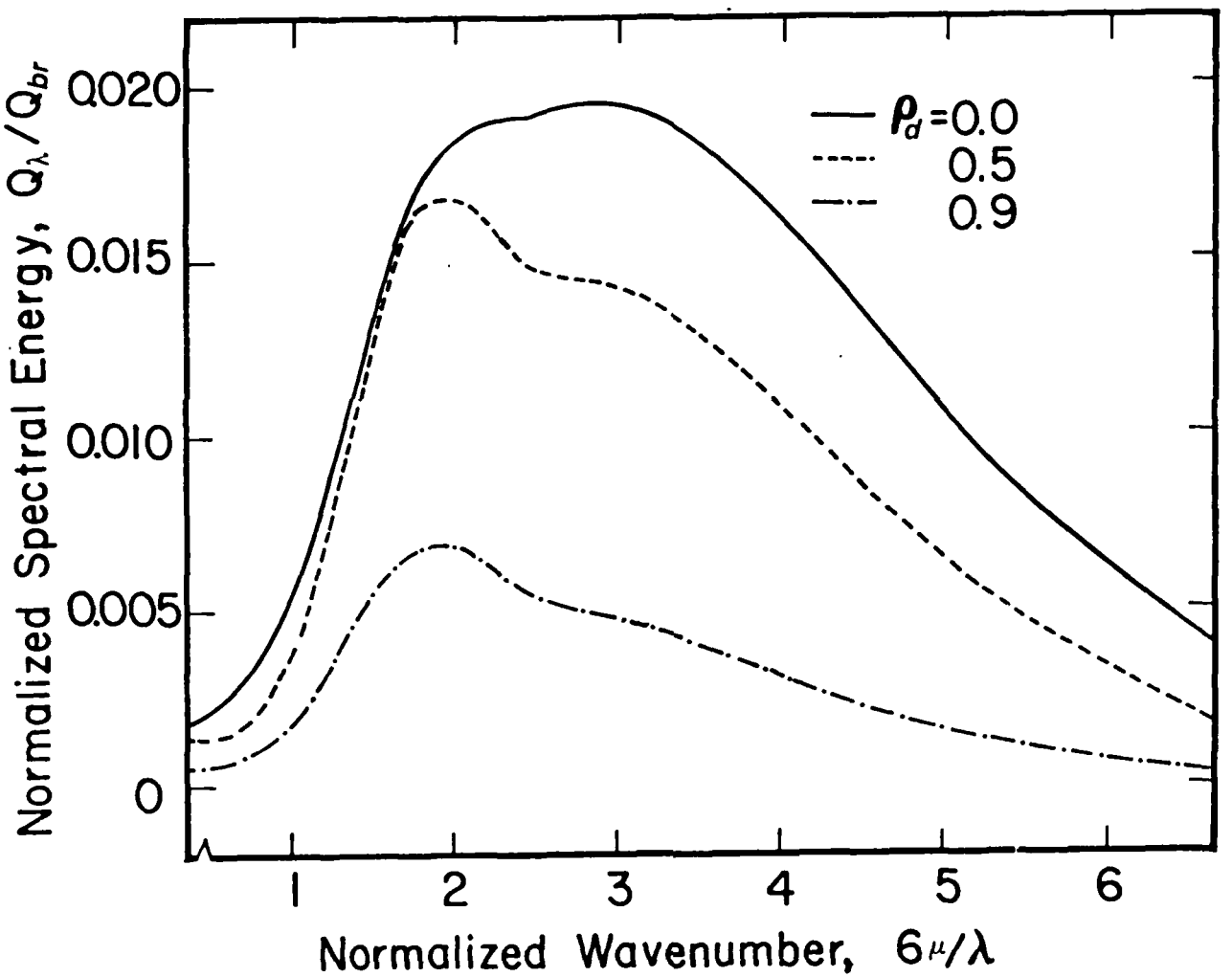


Fig. 3. Spectral radiation energy incident upon detectors located on the cylinder head at r = 0.0R, r = 0.5R and r = 0.9R.

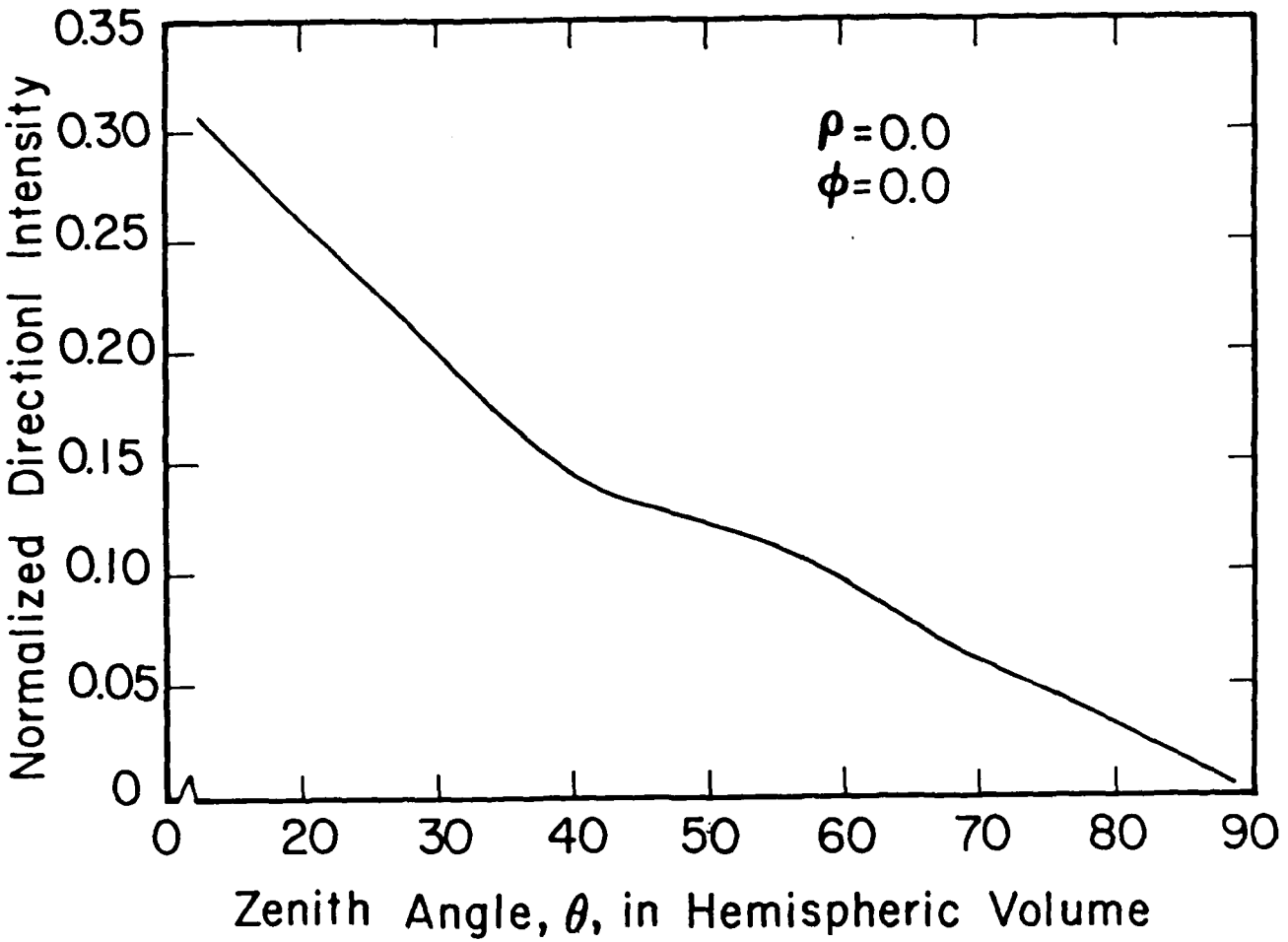


Fig. 4. Directional radiation intensity at the injection nozzle streaming through individual direction of zenith angle.

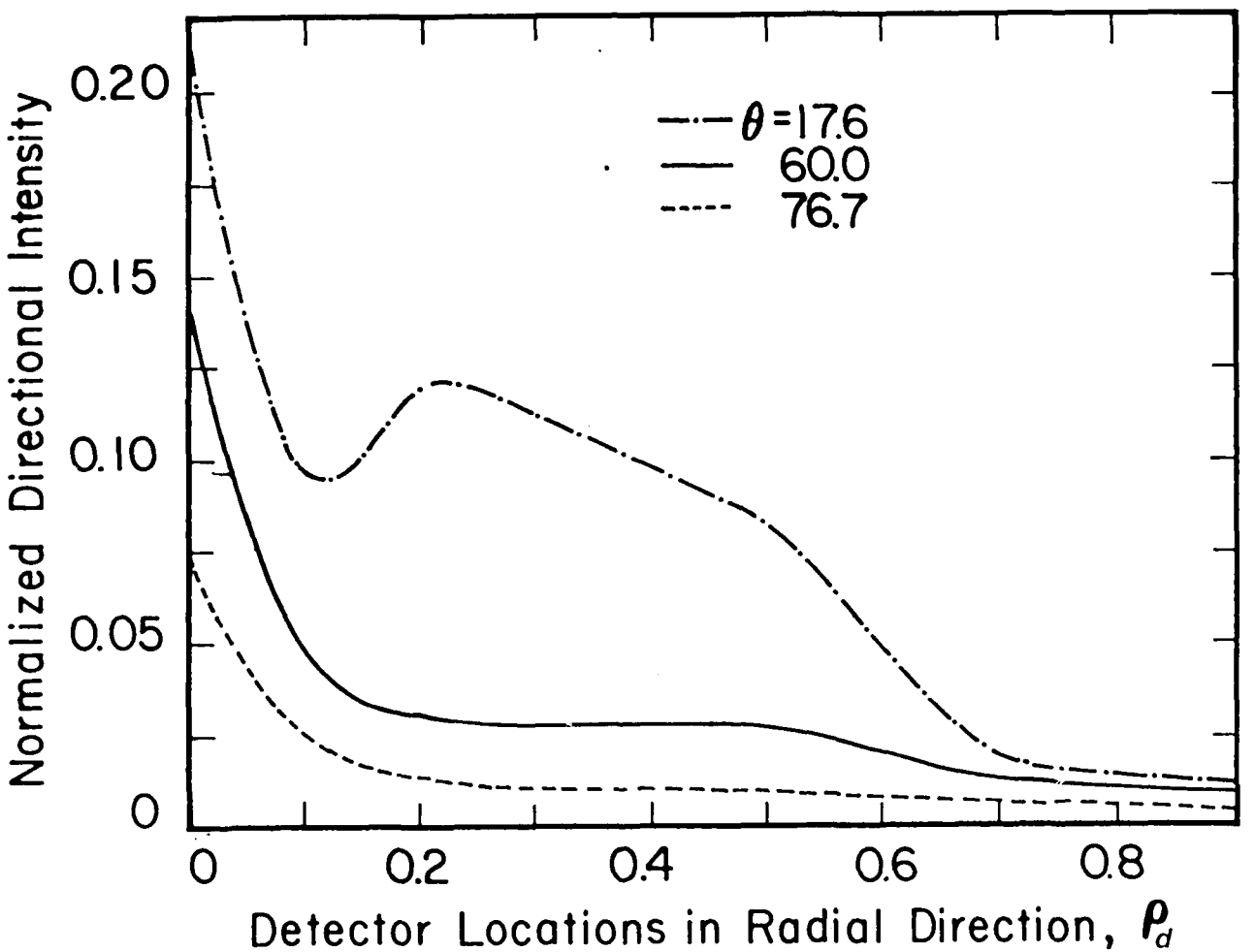
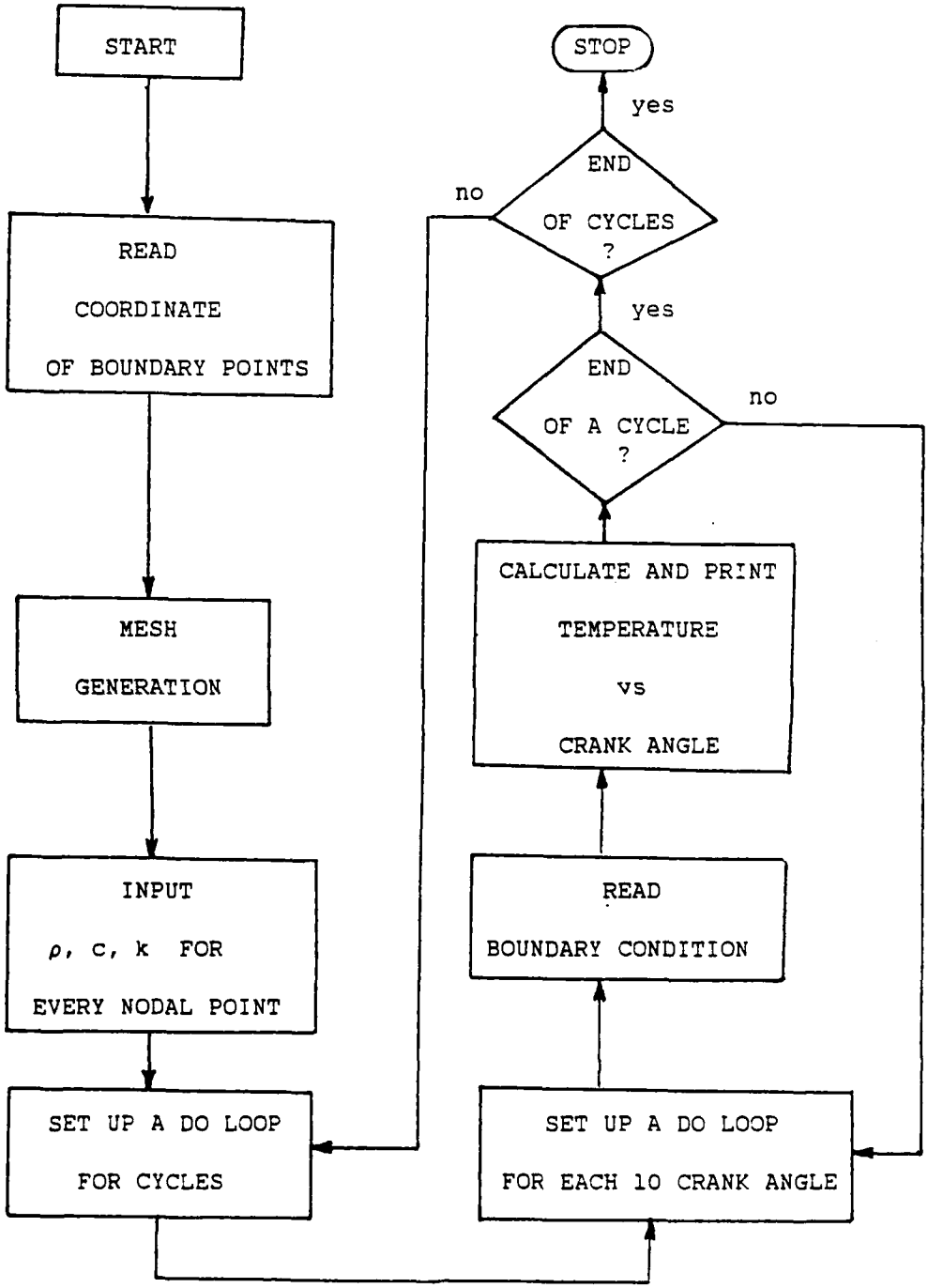


Fig. 5. Directional radiation intensity upon the cylinder head along the axis of the flame plume.

Flow Chart of HEATRAN



```
C*************************************************************************
C***                                                                   ***
C***            HEAT TRANSFER MODEL OF DIESEL COMBUSTION               ***
C***                                                                   ***
C***                                                                   ***
C***                                                                   ***
C***                                                                   ***
C***                                                                   ***
C***                                                                   ***
C***                                                                   ***
C*************************************************************************
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLK/RPM,RP,RL,RCS,CR,CM,HN,QC
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR2/CFRE(40),ERFC,ERFCL
      COMMON /BLKR6/SOCF(3),SOCG(3),SOCWN(3),VLGT
      COMMON /BLKR7/REFL,REFTP,REFQ,REFW,REFWL,CVLWL
      COMMON /BLKR8/OL,P,PE,T,TO,W
      COMMON /BLKR9/AE(20)
      COMMON /BLKV2/R(20),QV(20)
      COMMON /BLKT6/TM(360)
      COMMON /BLKC1/XC(60),YC(60),C(60),CK(60)
      COMMON /BLKC2/A(60,60),B(60,60)
      COMMON /BLKC3/D(60),UBD(60),UO(60),UB(60)
      COMMON /BLKC4/REFT,REFDT,REFC,REFK,REFLC,NPT,NU,NBC,NBCT,NLP
      COMMON /BLKC5/L1(80),L2(80),L3(80),I1(80),I2(80),I3(80),
     1              J1(80),J2(80),J3(80)
      DIMENSION UB1(60),QTT(11)
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>                  INPUT AND OUTPUT FORMATS                       <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
1     FORMAT(2F7.1,3E10.3,5I5)
2     FORMAT(2F10.4,2E10.3,F10.4)
3     FORMAT(9I5)
4     FORMAT(F10.5)
5     FORMAT(F9.3,F12.4)
6     FORMAT(F10.1)
7     FORMAT(7F7.1)
8     FORMAT(3(8E9.3,/),4E9.3)
C
C     INPUT COMMON PARAMETER
C
      READ(5,33)RPM,RP,RL,RCS,CR,CM,HN,QC
33    FORMAT(F7.1,3F9.3,3F9.1,F11.1)
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>                       CONSTANTS                                 <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      PI=4.D0*DATAN(1.D0)
      PIST=DSQRT(PI)
      PI4=PI*PI*PI*PI
      CALL ICFRE(40)
```

```
      REFQ=1.8805D2
      REFTP=2.4D3
      REFW=1.25D15
      REFWL=6.D0
      HCK=REFWL*REFTP*1.D-4
C>>>
C>>>  Disperion constants of soot optical constant from Lee & Tien.
C>>>
      SOCF(1)=7.2D26
      SOCF(2)=4.07D27
      SOCF(3)=4.47D28
      SOCG(1)=1.2D15
      SOCG(2)=5.9D15
      SOCG(3)=5.6D15
      SOCWN(1)=.0D0
      SOCWN(2)=1.25D15
      SOCWN(3)=7.25D15
      DO 100 I=1,3
         SOCF(I)=SOCF(I)*3.183D3/REFW/REFW
         SOCG(I)=SOCG(I)/REFW
100   SOCWN(I)=SOCWN(I)/REFW
      VLGT=2.9984D14/REFWL/REFW
      T0=1.D2/REFTP
      OMEG=.53D2
      TS=.5D3
C>>>
C>>>   Finite Difference constants of Conduction
C>>>
      READ(5,1) REFT,REFDT,REFC,REFK,REFLC,NPT,NLP,NU,NBC,NBCT
      READ(5,2) (XC(N),YC(N),C(N),CK(N),U0(N),N=1,NPT)
      READ(5,3) (L1(I),I1(I),J1(I),L2(I),I2(I),J2(I),L3(I),I3(I),
     +           J3(I),I=1,NLP)
C*************************************************************************
C***                                                                   ***
C***                          MAIN PROGRAM                             ***
C***                                                                   ***
C*************************************************************************
      CALL MATRIC
      CALL THERMO
      DO 200 K=10,50,10
         TG=TM(K)
         CALL CONV(OMEG,TG,TS)
         WRITE(6,5) ((R(I),QV(I)),I=1,11)
         WRITE(6,6) TM(K)
         CALL RANDO(CAD)
         WRITE(6,7) CAD,(AE(I),I=1,11)
         DO 120 M=1,11
120      QTT(M)=QV(M)/1.0D3+AE(M)*188.05D0
         IF(K.LE.10) GOTO 160
         READ(5,8) (UB1(L),L=1,NBC)
         DO 140 I=1,11
140      UB1(I+14)=QTT(I)
         TK0=(K-2)*1.D0/3.0D2
         TK=(K-1)*1.D0/3.0D2
         CALL COND(UB1,TK0,TK)
```

```
          GOTO 200
160       READ(5,8) (UB(L),L=1,NBC)
          DO 180 I=1,11
180     UB(I+14)=QTT(I)
200     CONTINUE
        STOP
        END
C*******************************************************************************
C***                                                                         ***
C***           HEAT RELEASE RATE MODEL OF DIESEL COMBUSTION                  ***
C***                                                                         ***
C***                              (THERMO)                                   ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C*******************************************************************************
        SUBROUTINE THERMO
        IMPLICIT REAL*8 (A-H,O-Z)
        COMMON /BLKT3/PG(360),WG(360)
        COMMON /BLKT4/PA,CA1,DCA,TAIR,RHM
        COMMON /BLK/RPM,RP,RL,RCS,CR,CM,HN,QC
        COMMON /BLKT5/XAIR(4),XR(4),XO(4),ZNAIR,ZNO
        COMMON /BLKT6/TM(360)
        COMMON /BLKT7/VMAXS(360)
        COMMON /BLKT8/SKG(360,2)
        COMMON /BLKT9/E(360)
        DIMENSION CAT(360),QX(360),DQX(360),XCO2T(360)
        DIMENSION PS(360,2),QS(360,2),DQS(360,2)
        DIMENSION PERS(2,5,5),ZN(4),CV(4),U(4),IDATE(3,5),ICYCLE(5)
1       FORMAT(6F9.3,F11.1)
2       FORMAT(I4)
3       FORMAT(5F9.3,I4,3I2)
4       FORMAT(10F8.2)
11      FORMAT(T5,'Engine parameter :',/,T8,'crank arm -',T28,F6.3,
     1' cm',/,T8,'connecting rod -',T28,F6.3,' cm',/,T8,'cylinder ',
     2'diemeter -',T28,F6.3,' cm',/,T8,'compression ratio -',T28,
     3F6.2,//,T5,'Fuel properties :',/,T8,'C:H -',T28,I2,':',I2,/,
     4T8,'low heat value -',T26,F9.0,' KJ/Kmole',/)
12      FORMAT('1','TEST :',I4,T20,'Date :',I2,'/',I2,'/',I2,//,T5,
     1'inlet press. -',T30,F6.1,' Kp',//,T5,'inlet temp. -',T30,
     2F6.1,' K',//,T5,'relative humidity -',T30,F6.1,' %',//,T5,
     3'initial sampling -',T30,F6.1,' deg.',//,T5,'sampling ',
     4'interval -', T30,F6.3,' deg.',//,T5,'engine speed -',
     5T30,F6.0,' rpm' )
13      FORMAT(/,' CYCLE :',I4,T30,'there are',I4,' pressure data ',
     1'in the cycle.',T80,'UNIT : CA=deg.;P=Kp',//,T4,'CA',T71,
     2T19,'CA',T26,'P',T34,'CA',T41,'P',T49,'CA',T56,'P',T64,'CA',
     3T71,'P',T79,'CA',T86,'P',T94,'CA',T101,'P',T109,'CA',T116,
     4'P',T11,'P')
```

```
14    FORMAT(8(2X,F5.1,2X,F6.1))
15    FORMAT(F5.0,6F11.3)
16    FORMAT(F5.0,3F11.3)
17    FORMAT(/,T5,'mean effective press. -',T30,F6.1,' Kp',/,
     1T5,'ind. horse power -',T30,F6.2,' HP',/,T5,'fuel air ratio',
     2' -',T30,F7.5,/,T5,'thermal efficiency -',T30,F6.1,' %',/,
     3T5,'deg. of const. vol. -',T30,F6.1,' %',/)
18    FORMAT(/,T5,'max. pressure ',F7.1,' Kp at ',F5.1,' deg. CA',/,
     1T5,'max. heat release rate ',F7.4,' kw/deg. at ',F5.1,
     2'deg. CA',/)
19    FORMAT('1',T20,'NORMALIZED PRESSURE vs CRANK ANGLE',/,T20,
     1'reference pressure - p" (psi)',/,T6,'P/P"',T17,'CA')
20    FORMAT('1',T20,'NORMALIZED RELEASED HEAT vs CRANK ANGLE',/,T20
     1,'reference released heat Q" (KJ)',/,T6,'Q/Q"',T17,'CA')
21    FORMAT('1',T20,'NORMALIZED HEAT RELEASED RATE vs CRANK ANGLE',/,
     1T20,'reference heat release rate - DQ"(KJ/deg.)',/,T4,'DQ/DQ"')
22    FORMAT('1',T7,'crank angle',T25,'pressure',T46,'heat release',
     1T60,'heat release rate',/,T10,'deg.',T27,'Kp',T50,'KJ',T65,
     2'KJ/deg.CA',/,T22,'ave.',T32,'S.D.',T42,'ave.',T52,'S.D.',/,
     3T64,'ave.',T74,'S.D.')
23    FORMAT(T10,F5.1,T20,F7.1,T30,F6.1,4(4X,F7.4))
24    FORMAT('1',/,T3,'The engine  performance in the tests :',/,
     1T4,'Date',T13,'Cycles',T29,'imep',T46,'ind. HP',T69,'F/A',
     2T86,'efficiency',T103,'deg. of const. vol.',/,T25,'ave.',T35,
     3'S.D.',T45,'ave.',T55,'S.D.',T65,'ave.',T75,'S.D.',T85,'ave.',
     4T95,'S.D.',T105,'ave.',T115,'S.D.',/)
25    FORMAT(2X,I2,'/',I2,'/',I2,4X,I4,3X,5(F10.2,F10.3))
      MC=CM
      NH=HN
      WRITE(6,11)RCS,RL,RP,CR,MC,HN,QC
      ITEST=0
      READ(5,2)INDEX1
100   INDEX1=INDEX1-1
      IF( INDEX1 .LT. 0 ) GOTO 800
200   ITEST=ITEST+1
      ICYCLE(ITEST)=0
      READ(5,3)PA,TAIR,RHM,CA1,DCA,ISAMP,(IDATE(M,ITEST),M=1,3)
      WRITE(6,12)ITEST,(IDATE(M,ITEST),M=1,3),PA,TAIR,RHM,CA1,DCA,RPM
      READ(5,2)INDEX2
300   INDEX2=INDEX2-1
      IF( INDEX2 .LT. 0 ) GOTO 700
      DO 350 I=1,ISAMP
350   E(I)=CA1+(I-1)*DCA
      ICYCLE(ITEST)=ICYCLE(ITEST)+1
      READ(5,4)(PG(I),I=1,ISAMP)
      WRITE(6,13)ICYCLE(ITEST),ISAMP
      WRITE(6,14)(E(J),PG(J),J=1,ISAMP)
      CALL PERFOR(ISAMP,PIME,HPI,FATH,EFF,DCV)
      CAT(1)=CA1
      DO 400 J=2,ISAMP
         CAT(J)=CA1+(J-1)*DCA
         CALL VOLUME(CAT(J),V,DV)
         TM(J)=PG(J)*V/((ZN0+.25D0*HN*E(J-1))*8.314D6)
         CALL SPHEAT(TM(J),CV,U)
         E(ISAMP+1)=0.D0
```

```
          DQX(J)=(E(J+1)-E(J-1))*QC/2.D0*DCA
          QX(J)=E(J)*QC
          ZNT=ZN0*(1.+.25D0*HN*E(J))
          XCO2T(J)=(ZN0*X0(3)+HN*E(J))/ZNT
400       WRITE(6,15)CAT(J),PG(J),V,TM(J),DQX(J),QX(J),XCO2T(J)
          DO 500 J=51,210
          CAT(J)=(CA1+ISAMP*DCA)+(J-51)*DCA
          ZNL=ZN0*(1.D0+.25D0*HN*E(ISAMP))
          ZN(1)=ZN0*X0(1)-(CM+.25D0*HN)*E(ISAMP)
          ZN(2)=ZN0*X0(2)
          ZN(3)=ZN0*X0(3)+CM*E(ISAMP)
          ZN(4)=ZN0*X0(4)+.5D5*HN*E(ISAMP)
          CALL SPHEAT(TM(J-1),CV,U)
          CALL VOLUME(CAT(J),V,DVL)
          ACV=CV(1)*ZN(1)+CV(2)*ZN(2)+CV(3)*ZN(3)+CV(4)*ZN(4)
          TM(J)=TM(J-1)-PG(J-1)*DVL*DCA/ACV/1.D6
          PG(J)=ZNL*8.314D6*TM(J)/V
500       WRITE(6,16)CAT(J),PG(J),V,TM(J)
          WRITE(6,17)PIME,HPI,FATH,EFF,DCV
600       ICT=ICYCLE(ITEST)
          CALL STATIS(PERS(1,1,ICT),PERS(2,1,ICT),ICT,PIME)
          CALL STATIS(PERS(1,2,ICT),PERS(2,2,ICT),ICT,HPI)
          CALL STATIS(PERS(1,3,ICT),PERS(2,3,ICT),ICT,FATH)
          CALL STATIS(PERS(1,4,ICT),PERS(2,4,ICT),ICT,EFF)
          CALL STATIS(PERS(1,5,ICT),PERS(2,5,ICT),ICT,DCV)
          DO 620 L=1,ISAMP
          CALL STATIS(PS(L,1),PS(L,2),ICT,PG(L))
          E(L)=E(L)*QC
620       CALL STATIS(QS(L,1),QS(L,2),ICT,E(L))
          DO 630 I=1,ISAMP
630       VMAXS(I)=PG(I)
          CALL VMAX(ISAMP,PMAX,LPMAX)
          CAPMAX=CA1+(LPMAX-1)*DCA
          DQS(1,1)=0.D0
          DQS(1,2)=0.D0
          DQS(ISAMP,1)=0.D0
          DQS(ISAMP,2)=0.D0
          ISAMP1=ISAMP-1
          DO 640 L=2,ISAMP1
          DQ=(E(L+1)-E(L-1))/(2.D0*DCA)
          IF( DQ .LT. 0.D0 ) DQ=0.D0
          WG(L)=DQ
640       CALL STATIS(DQS(L,1),DQS(L,2),ICT,DQ)
          WG(1)=0.D0
          WG(ISAMP)=0.D0
          DO 650 I=1,ISAMP
650       VMAXS(I)=WG(I)
          CALL VMAX(ISAMP,DQMAX,LDQMAX)
          CADQM=CA1+(LDQMAX-1)*DCA
          WRITE(6,18)PMAX,CAPMAX,DQMAX,CADQM
          GO TO 300
700       WRITE(6,19)
          DO 710 I=1,ISAMP
          SKG(I,1)=PS(I,1)
710       SKG(I,2)=PS(I,2)
```

```
      CALL SKETCH(ISAMP,DCA,CA1)
      WRITE(6,20)
      DO 720 I=1,ISAMP
         SKG(I,1)=QS(I,1)
720   SKG(I,2)=QS(I,2)
      CALL SKETCH(ISAMP,DCA,CA1)
      WRITE(6,21)
      DO 730 I=1,ISAMP
         SKG(I,1)=DQS(I,1)
730   SKG(I,2)=DQS(I,2)
      CALL SKETCH(ISAMP,DCA,CA1)
      WRITE(6,22)
      DO 750 I=1,ISAMP
         CA=CA1+(I-1)*DCA
         WRITE(6,23) CA,PS(I,1),PS(I,2),QS(I,1),QS(I,2),
     +               DQS(I,1),DQS(I,2)
         PG(I)=PS(I,1)
750   WG(I)=DQS(I,1)
      DO 760 I=1,ISAMP
760   VMAXS(I)=PG(I)
      CALL VMAX(ISAMP,PMAX,LPMAX)
      DO 770 I=1,ISAMP
770   VMAXS(I)=WG(I)
      CALL VMAX(ISAMP,DQMAX,LDQMAX)
      CAPMAX=CA1+(LPMAX-1)*DCA
      CADQM=CA1+(LDQMAX-1)*DCA
      WRITE(6,18)PMAX,CAPMAX,DQMAX,CADQM
      GO TO 100
800   WRITE(6,23)
      DO 850 K=1,ITEST
850   WRITE(6,25) (IDATE(M,K),M=1,3),ICYCLE(K),((PERS(I,J,K),I=1,2),
     1J=1,5)
      RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>            SPECIFIC HEAT AND INTERNAL ENERGY                    <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE SPHEAT(T,CV,U)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION CV(4),U(4)
1     FORMAT(T20,'ERROR:SPHEAT - Temp.=',E12.5)
      IF( T .GT. 0.D0 ) GOTO 200
      WRITE(6,1)T
      STOP
200   T18=T*1.8D0
      T18ST=DSQRT(T18)
      T18SQ=T18*T18
      Z19=1.986D0
      Z83=8.3143D0/Z19
      Z8318=Z83/1.8D0
      Z54=5.4D2
      Z54ST=DSQRT(Z54)
      Z54SQ=Z54*Z54
```

```
      Z18LG=DLOG(T18/Z54)
      CV(1)=(1.1515D1-1.72D2/T18ST+1.53D3/T18-Z19)*Z83
      CV(2)=(9.47D0-3.47D3/T18+1.16D6/T18SQ-Z19)*Z83
      CV(3)=(1.62D1-6.52D3/T18+1.41D6/T18SQ-Z19)*Z83
      CV(4)=(1.998D1-5.67D2/T18ST+7.5D3/T18-Z19)*Z83
      U(1)=(9.528D0*(T18-Z54)-3.44D2*(T18ST-Z54ST)+1.53D3*Z18LG)*Z8318
      U(2)=(7.483D0*(T18-Z54)-3.47D3*Z18LG-1.16D6/T18+
     1      1.16D6/Z54)*Z8318
      U(3)=(14.213D0*(T18-Z54)-3.47D3*Z18LG-1.41D6*
     1      (1.D0/T18-1.D0/Z54))*Z8318
      U(4)=(1.7873D1*(T18-Z54)-1.194D3*(T18ST-Z54ST)
     1     +7.5D3*Z18LG)*Z8318
      IF ( T18 .LT. 4.D3 ) GOTO 900
      CV(1)=(CV(1)+.5D-5*(T18-4.D3))*Z83
      U(1)=(U(1)+.5D-4*(.5D0*(T18SQ-Z54SQ)-4.D3*(T18-Z54)))*Z8318
900   RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>              VOLUME OF COMBUSTION CHAMBER                       <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE VOLUME(CA,V,DV)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLK/RPM,RP,RL,RCS,CR,CM,HN,QC
100   IF( CA .GE. 0.D0 ) GOTO 200
      CA=CA+3.6D2
      GO TO 100
200   IF( CA .LE. 3.6D2) GOTO 400
      CA=CA-3.6D2
      GO TO 200
400   THETA=CA*PI/1.8D2
      A=PI*RP*RP
      VC=A*2.D0*RCS/(CR-1.D0)
      X1=DSQRT(1.D0-(RCS*DSIN(THETA)/RL)**2)
      V=(RCS*(1.D0+DCOS(THETA))+RL*(1.D0-X1))*A+VC
      DV=(RCS*RCS*DSIN(2.D0*THETA)/(2.D0*RL*RL*X1)-RCS*
     1   DSIN(THETA))*A*PI/1.8D2
      RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>                        PISTON WORK                              <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE WORK(CA1,DCA,NO)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKT3/PG(360),WG(360)
      WG(1)=0.D0
      DO 100 J=2,NO
         CA=CA1+(J-1)*DCA
         CA0=CA-DCA
         CALL VOLUME(CA0,V0,DV0)
         CALL VOLUME(CA,V,DV)
```

```
          DW=(PG(J)*DV+PG(J-1)*DV0)*DCA/2.D6
100     WG(J)=WG(J-1)+DW
        RETURN
        END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                        AIR COMPOSITION                            <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
        SUBROUTINE AIR(TAIR,PA,RHM)
        IMPLICIT REAL*8 (A-H,O-Z)
        COMMON /BLKT5/XAIR(4),XR(4),XO(4),ZNAIR,ZNO
        DIMENSION B(5),F(5)
        DATA F/.17803D0,.2563D0,.3632D0,.5073D0,.6988D0/
        R=(1.8D0*TAIR-5.3D2)/1.D1
        B(1)=R*(R*R-1.D0)*(R-2.D0)/2.4D1
        B(2)=-R*(R-1.D0)*(R*R-4.D0)/6.D0
        B(3)=(R*R-1.D0)*(R*R-4.D0)/4.D0
        B(4)=-R*(R+1.D0)*(R*R-4.D0)/6.D0
        B(5)=R*(R*R-1.D0)*(R+2.D0)/2.4D1
        PVS=0.D0
        DO 100 I=1,5
100     PVS=PVS+B(I)*F(I)
        PV=RHM*PVS/1.D2
        ASH=PV/(PA-PV)
        XAIR(1)=.2099D0/(1.D0+ASH)
        XAIR(2)=.7898D0/(1.D0+ASH)
        XAIR(3)=.3D-3/(1.D0+ASH)
        XAIR(4)=ASH/(1.D0+ASH)
        RETURN
        END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                        FUEL CONSUMPTION                           <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
        SUBROUTINE EXTENT(TR,ISAMP,TBDC,T1)
        IMPLICIT REAL*8 (A-H,O-Z)
        COMMON /BLKT3/PG(360),WG(360)
        COMMON /BLKT9/E(360)
        COMMON /BLKT4/PA,CA1,DCA,TAIR,RHM
        COMMON /BLK/RPM,RP,RL,RCS,CR,CM,HN,QC
        COMMON /BLKT5/XAIR(4),XR(4),XO(4),ZNAIR,ZNO
        DIMENSION CV(4),U(4)
        BETA=1.D0/CR
        TBDC=(TAIR+BETA*TR)/(1.D0+BETA)
        CALL VOLUME(0.D0,V0,DV0)
        ZNO=PA*V0/(8.314D6*TBDC)
        ZNAIR=ZNO/(1.D0+BETA)
        ZNR=ZNAIR*BETA
        CALL VOLUME(CA1,V1,DV1)
        T1=PG(1)*V1/(8.314D6*ZNO)
        CALL SPHEAT(T1,CV,U)
        U1=0.D0
        DO 100 K=1,4
```

```
          X0(K)=(ZNAIR*XAIR(K)+ZNR*XR(K))/ZN0
100       U1=U1+ZN0*X0(K)*U(K)
          CALL WORK(CA1,DCA,ISAMP)
          E(1)=0.D0
          DO 400 J=2,ISAMP
             CA=CA1+(J-1)*DCA
             CALL VOLUME(CA,V,DV)
             T=PG(J)*V/((ZN0+.25D0*HN*E(J-1))*8.314D6)
             CALL SPHEAT(T,CV,U)
             E(J)=(ZN0*(X0(1)*U(1)+X0(2)*U(2)+X0(3)*U(3)+X0(4)*U(4))-U1+
         1         WG(J))/(QC+(CM+.25D0*HN)*U(1)-CM*U(3)-.5D0*HN*U(4))
          IF ( E(J) .LT. 0.D0 ) E(J)=0.D0
             IF( E(J) .GT. ZN0*X0(1)/(CM+.25D0*HN) )
         +           E(J)=ZN0*X0(1)/(CM+.25D0*HN)
400       CONTINUE
          RETURN
          END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                      ENGINE PERFORMANCE                           <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
          SUBROUTINE PERFOR(ISAMP,PIME,HPI,FATH,EFF,DCV)
          IMPLICIT REAL*8 (A-H,O-Z)
          DIMENSION ZN(4),U(4),CV(4)
          COMMON /BLKT3/PG(360),WG(360)
          COMMON /BLKT9/E(360)
          COMMON /BLKT4/PA,CA1,DCA,TAIR,RHM
          COMMON /BLK/RPM,RP,RL,RCS,CR,CM,HN,QC
          COMMON /BLKT5/XAIR(4),XR(4),X0(4),ZNAIR,ZN0
1         FORMAT(/,T5,'K=',I3,/,T5,'The assumed residual gas temperatu',
         1're ','TR=',F6.1,/,T30,'compositions XO2=',F6.4,' XN2=',F6.4,
         2'XCO2','=',F6.4,' XH2O=',F6.4,/)
100       K=0
          CALL AIR(TAIR,PA,RHM)
200       TR=TAIR
          DO 250 I=1,4
250       XR(I)=XAIR(I)
300       K=K+1
320       WRITE(6,1)K,TR,XR
350       CALL EXTENT(TR,ISAMP,TBDC,T1)
400       ZNL=ZN0*(1.D0+.25D0*HN*E(ISAMP))
          ZN(1)=ZN0*X0(1)-(CM+.25D0*HN)*E(ISAMP)
          ZN(2)=ZN0*X0(2)
          ZN(3)=ZN0*X0(3)+CM*E(ISAMP)
          ZN(4)=ZN0*X0(4)+.5D0*HN*E(ISAMP)
          CAL=CA1+(ISAMP-1)*DCA
          CALL VOLUME(CAL,VL,DVL)
          TL=PG(ISAMP)*VL/(8.314D6*ZNL)
          DCAL=(3.6D2-CAL)/1.D2
          CALL SPHEAT(TL,CV,U)
          UL=U(1)*ZN(1)+U(2)*ZN(2)+U(3)*ZN(3)+U(4)*ZN(4)
          PL=PG(ISAMP)
          DO 450 I=1,100
             CALL SPHEAT(TL,CV,U)
```

```
          ACV=CV(1)*ZN(1)+CV(2)*ZN(2)+CV(3)*ZN(3)+CV(4)*ZN(4)
          TL=TL-PL*DVL*DCAL/ACV/1.D6
          CA=CAL+I*DCAL
          CALL VOLUME(CA,VL,DVL)
450     PL=ZNL*8.314D6*TL/VL
        IF(DABS(TR-TL)-5.D0)600,600,460
460     IF(K-10)500,500,600
500     TR=TL
        DO 550 I=1,4
550     XR(I)=ZN(I)/ZNL
        GO TO 300
600     IT=(.18D3-CA1)/DCA
        CATDC=CA1+IT*DCA
        WTDC=WG(IT)+(WG(IT+1)-WG(IT))*(.18D3-CATDC)/DCA
        UB=ZN(1)*U(1)+ZN(2)*U(2)+ZN(3)*U(3)+ZN(4)*U(4)
        CALL VOLUME(0.D0,VB,DVB)
        CALL VOLUME(.18D3,VT,DVT)
        PIME=(WG(ISAMP)-WTDC+UL-UB)/(VB-VT)*1.D6
        EFFV=(1.D0-1.D0/CR**.4D0)*1.D2
        FATH=(1.2D1*CM+HN)*E(ISAMP)/(2.8967D1*ZN0)
        CALL SPHEAT(TAIR,CV,U)
        UTBDC=X0(1)*U(1)+X0(2)*U(2)+X0(3)*U(3)+X0(4)*U(4)
        CALL SPHEAT(T1,CV,U)
        UT1=X0(1)*U(1)+X0(2)*U(2)+X0(3)*U(3)+X0(4)*U(4)
        WALL=ZN0*(UTBDC-UT1)+WG(ISAMP)+UL-UB
        HPI=WALL*RPM/(.7457D0*6.D1)
        QALL=QC*E(ISAMP)
        EFF=WALL*1.D2/QALL
        DCV=EFF*1.D2/EFFV
        RETURN
        END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                    STATISTICAL ANALYSIS                           <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
        SUBROUTINE STATIS(AVE1,SD1,N,SAMP)
        IMPLICIT REAL*8 (A-H,O-Z)
        IF ( N .GT. 1 ) GOTO 100
        AVE1=SAMP
        SD1=0.D0
        GO TO 900
100     AVE2=(N-1)*AVE1/N+SAMP/N
        SD1=SD1**2*(N-2)/(N-1)
        SD1=SD1+(AVE1-AVE2)**2/(N-1)+((SAMP-AVE2)**2)/(N-1)
        IF(SD1)200,400,300
200     SD1=DABS(SD1)
300     SD1=DSQRT(SD1)
400     AVE1=AVE2
900     RETURN
        END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                THE MAXIMUM OF A SERIES                            <<<
C>>>                                                                   <<<
```

```
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE VMAX(NO,SMAX,LSMAX)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKT7/S(360)
      LSMAX=1
      SMAX=S(1)
      IF( NO .LE. 1 ) GOTO 900
      DO 100 I=2,NO
         IF( SMAX .GE. S(I) ) GOTO 100
         SMAX=S(I)
         LSMAX=I
100   CONTINUE
900   RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                        SKETCH                                     <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE SKETCH(NO,DCA,CA1)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKT8/G(360,2)
      INTEGER F(101),BLANK,DASH,TAB,DOT,STAR
      DATA BLANK,DASH,TAB,DOT,STAR/' ','_','|','+','*'/
1     FORMAT(2X,'ave.',3X,'S.D. (deg.)',101A1)
2     FORMAT(1X,F6.4,1X,F6.4,1X,F5.1,101A1)
3     FORMAT(//,T20,'The reference unit value = ',E12.6,//)
      DO 100 I=1,101
100   F(I)=DASH
      WRITE(6,1)F
      F(1)=TAB
      DO 160 J=2,101
160   F(J)=BLANK
      UMAX=DABS(G(1,1))+DABS(G(1,1))
      REF=G(1,1)
      DO 300 K=2,NO
         TEM=DABS(G(K,1))+DABS(G(K,2))
         IF( UMAX .LT. TEM ) UMAX=TEM
         IF( REF .LT. DABS(G(K,1)) ) REF=DABS(G(K,1))
300   CONTINUE
      DO 500 L=1,NO
         GLINE=DABS(G(L,1)/UMAX)
         LINE=GLINE*1.D2+1
         IF ( LINE .LT. 2 ) LINE=2
         IF( LINE .GT. 101 ) LINE=101
         SL=DABS(G(L,2)/UMAX)
         LS1=LINE+SL*1.D2
         IF ( LS2 .LT. 2 ) LS2=2
         IF ( LS1 .GT. 101 ) LS1=101
         LS2=LINE-SL*1.D2
         IF ( LS2 .LT. 2 ) LS2=2
         IF ( LS2 .GT. 101 ) LS2=101
         F(LS1)=DOT
         F(LS2)=DOT
         F(LINE)=STAR
```

```
          CA=CA1+(L-1)*DCA
          GLINE=G(L,1)/REF
          SL=G(L,2)/REF
          WRITE(6,2)GLINE,SL,CA,F
          F(LINE)=BLANK
          F(LS1)=BLANK
500       F(LS2)=BLANK
          WRITE(6,3)REF
          RETURN
          END
C*******************************************************************************
C***                                                                         ***
C***        CONVECTION HEAT TRANSFER MODEL OF DIESEL COMBUSTION              ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C*******************************************************************************
          SUBROUTINE CONV(OMEG,TG,TS)
          IMPLICIT REAL*8 (A-H,O-Z)
          COMMON /BLKV2/R(20),QV(20)
          COMMON /BLK/RPM,RP,RL,RCS,CR,CM,HN,QC
          R(1)=0.D0
          QV(1)=0.D0
          CALL PROPER(TG,RKG,VG)
          DO 100 I=2,11
             R(I)=.1D0*(I-1)*RP
             RE=2.D0*OMEG*R(I)*R(I)/VG
          QV(I)=.47D-1*RKG/R(I)*RE**.8D0*.7D0**.33D0*(TG-TS)
          QV(I)=QV(I)/1.8805D2
100        R(I)=0.1D0*(I-1)
          RETURN
          END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                     <<<
C>>>                        FLUID PROPERTIES                             <<<
C>>>                                                                     <<<
C>>>-------------------------------------------------------------------<<<
          SUBROUTINE PROPER(T,RKG,VG)
          IMPLICIT REAL*8 (A-H,O-Z)
          DIMENSION RKGV(7),VGV(7),TV(7)
          DATA RKGV/3.95D0,5.13D0,6.25D0,7.32D0,8.37D0,9.46D0,1.11D1/
          DATA VGV/3.79D-1,6.64D-1,9.9D-1,1.38D+0,1.82D+0,2.29D+0,3.1D+0/
          DATA TV/5.D2,7.D2,9.D2,1.1D3,1.3D3,1.5D3,1.8D3/
          RKG=RKGV(1)
          VG=VGV(1)
          IF ( T .LT. TV(1) ) GOTO 900
          DO 100 I=2,7
             IF ( T .LT. TV(I) ) GOTO 200
100       CONTINUE
          RKG=RKGV(7)
          VG=VGV(7)
```

```
      GOTO 900
200   RKG=RKGV(I-1)+(RKGV(I)-RKGV(I-1))/(TV(I)-TV(I-1))*(T-TV(I-1))
      VG=VGV(I-1)+(VGV(I)-VGV(I-1))/(TV(I)-TV(I-1))*(T-TV(I-1))
900   RETURN
      END
C*******************************************************************************
C***                                                                         ***
C***        RADIATION HEAT TRANSFER MODEL OF DIESEL COMBUSTION               ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C*******************************************************************************
      SUBROUTINE RANDO(CAD)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR3/FVF,FVA,FVB,FVC,FAF,FAA,FAB,FAC,XHF,XHA,XHB,XHC,
     +              XCF,XCA,XCB,XCC
      COMMON /BLKR4/RHODN,PHIDN,ZDN,THEIN,OMES,RNZ,VS,NFP
      COMMON /BLKR5/RCB,ZCB,ZCC,ZCCB,RP
      COMMON /BLKR7/REFL,REFTP,REFQ,REFW,REFWL,CVLWL
      COMMON /BLKR8/OL,P,PE,T,TO,W
      COMMON /BLKR9/AE(20)
      COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
      COMMON /BLKRD/TSCH,TSCW,TSP,TSB,ES
      DIMENSION SAE(10)
C>>>-----------------------------------------------------------------------<<<
C>>>                                                                       <<<
C>>>                        I/O FORMATS                                    <<<
C>>>                                                                       <<<
C>>>-----------------------------------------------------------------------<<<
10    FORMAT(6F10.4,/,F10.4,E10.3,2F10.4,4I5,/,2I5,3F10.4,/,5F10.4,
     +       E10.3)
11    FORMAT(F10.4)
12    FORMAT(F10.4,E10.3,3F10.4,/,3(10X,4F10.4,/))
20    FORMAT(' Engine speed = ',F5.0,' rpm',/,' Combustion bowl ',
     +'radius = ',F6.4,' cm',/,' Compression ratio = ',F4.1,/,
     +' Piston radius = ',F6.2,' cm',/,' Crank sheft length = ',
     +F6.2,' cm',/,' Connection rod length = ',F6.2,' cm',//,
     +' Fuel injection rate = ',F6.4,' cu. cm/sec',/,' Injection'
     +,' nozzle radius = ',F6.4,' cm',/,' Incline angle = ',F4.1,
     +' deg',/,' Swirl ratio = ',F4.1,/,' Fuel compostion - ( ',
     +'C:H:O = ',I2,':',I2,':',I2,' )',/,' # of plumes = ',I2,//)
21    FORMAT(1X,'Flame temperature - AFT',/,
     +' Surface temperature at',/,'  combustion'
     +,' bowl - ',F5.0,'K',/,'  cylinder head   - ',F5.0,'K',/,
     +'  cylinder wall   - ',F5.0,'K',/,'  piston surface  - ',
     +F5.0,'K',//,' Surface emissivity = ',F4.2,/,' Length and'
     +,' wavelength convertor = ',F10.0,' um/cm',/)
22    FORMAT(' Engine crank angle = ',F6.1,' deg,   Piston',
     +' location : ',F6.4,' cm',/)
23    FORMAT(' Cylinder pressure = ',F6.1,' KN/cm/cm',/,' Distr',
```

```
     +'ibution paramters of',/,'  soot volume fraction  -',E10.2,
     +3F10.2,/,'  burnt fuel/air ratio  -',F10.4,3F10.2,/,'  molar',
     +' fraction of H2O -',F10.4,3F10.2,/,20X,'CO2 -',F10.4,3F10.2)
24    FORMAT(/,4X,'CA = ',F7.2,' deg.,  P = ',F6.2,' atm,',/,4X,
     +'fv = ',E10.3,',  F/A = ',F8.5,',  XH2O = ',F8.5,',  XCO2 = ',
     +F8.5,/)
25    FORMAT(4X,'Spectral AE = ',5E10.3,/,18X,5E10.3,/,4X,'Apparent'
     +,' Emissivity = ',F8.5,/)
26    FORMAT(1X,'Detector''s location - (',F4.1,',',F4.0,',',F4.1,
     +')')
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>     INPUT : engine speed (RPM), radius of combustion chamber    <<<
C>>>             (RCB), compression ratio (CR), piston radius (RP)   <<<
C>>>             length of engine crank sheft and connection rod     <<<
C>>>             (RCS,RL), fuel injection rate (FIR), injection      <<<
C>>>             nozzle radius (RNZ), fuel injection angle (THEIN)   <<<
C>>>             , swirl ratio (OMES), fuel composition (CM,HN,OI)   <<<
C>>>             , # of fuel plumes (NFP), detector's location       <<<
C>>>             (RHODN,PHIDN,ZDN), surface temperatures (TSB,       <<<
C>>>             TSCH,TSCW,TSP), surface emissivity (ES) and         <<<
C>>>             unit convertion factor (CVLWL).                     <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      READ(5,10)RPM,RCB,CR,RP,RCS,RL
     +          ,FIR,RNZ,THEIN,OMES,MC,NH,IO,NFP
     +          ,NTHE,NOP,RHODN,PHIDN,ZDN
     +          ,TSB,TSCH,TSCW,TSP,ES,CVLWL
      WRITE(6,20)RPM,RCB,CR,RP,RCS,RL
     +          ,FIR,RNZ,THEIN,OMES,MC,NH,IO,NFP
      WRITE(6,21)TSB,TSCH,TSCW,TSP,ES,CVLWL
      CM=MC
      HN=NH
      OI=IO
      REFL=RP
C>>>
C>>>  Normalize variables by reference unit.
C>>>
      RP=RP/REFL
      RCB=RCB/REFL
      RCS=RCS/REFL
      RL=RL/REFL
      RNZ=RNZ/REFL
      THEIN=THEIN*PI/.18D3
      RHODN=RHODN/REFL
      PHIDN=PHIDN*PI/.18D3
      ZDN=ZDN/REFL
      ZCB=2.D0*RP*RP*RCS/RCB/RCB/(CR-1.D0)
      FIR=FIR/REFL/REFL/REFL
      VS=FIR/PI/RNZ/RNZ/NFP
      OMES=OMES*RPM*PI/3.D1
      TSB=TSB/REFTP
      TSCH=TSCH/REFTP
      TSCW=TSCW/REFTP
      TSP=TSP/REFTP
```

```
      STHEIN=DSIN(THEIN)
      CTHEIN=DCOS(THEIN)
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>     CHECK if data ends - READ engine crank angle (deg)            <<<
C>>>           IF CA > 0, go on computing                              <<<
C>>>           IF CA <= 0, stop.                                       <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      READ(5,11)CAD
      IF ( CAD .LE. 0.D0 ) GOTO 900
      CA=CAD*PI/.18D3
      CW=DSQRT(1.D0-RCS*RCS/RL/RL*DSIN(CA)**2)
      ZCC=2.D0*RCS-(RL*CW-RCS*DCOS(CA)+RCS-RL)
      ZCCB=ZCC+ZCB
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>     READ cylinder pressure (P), distribution parameters           <<<
C>>>          of soot volume fraction (FVF,FVA,FVB,FVC), burnt         <<<
C>>>          fuel/air ratio (FAF,FAA,FAB,FAC), water vapor (          <<<
C>>>          (XHF,XHA,XHB,XHC), and carbon dioxide (XCF,XCA,          <<<
C>>>          XCB,XCC)                                                 <<<
C>>>-------------------------------------------------------------------<<<
      READ(5,12)P,FVF,FVA,FVB,FVC,FAF,FAA,FAB,FAC
     +          ,XHF,XHA,XHB,XHC,XCF,XCA,XCB,XCC
      WRITE(6,23)P,FVF,FVA,FVB,FVC,FAF,FAA,FAB,FAC
     +           ,XHF,XHA,XHB,XHC,XCF,XCA,XCB,XCC
      REFP=1.03323D0
      P=P/REFP
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>     COMPUTE time-resolved radiation heat flux from                <<<
C>>>             in-cylinder species to detector (RHF)                 <<<
C>>>     WRITE engine crank angle (CA), mean soot volume fraction      <<<
C>>>           (FVM), mean burnt fuel/air ratio (FAM), mean molar      <<<
C>>>           fraction of water vapor (XHM), mean molar fraction      <<<
C>>>           of carbon dioxide (XCM), and apparent emissivity        <<<
C>>>           (AE)                                                    <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      DO 800 I=1,11
         RHODN=.1D0*(I-1)
         ZDN=0.D0
         DO 800 J=1,1
            PHIDN=.5D1*(J-1)
            CALL XMEAN(FVM,FAM,XHM,XCM)
            IF ( I .LE. 1 ) WRITE(6,24)CAD,P,FVM,FAM,XHM,XCM
            WRITE(6,26)RHODN,PHIDN,ZDN
            PHIDN=PHIDN*PI/.18D3
            AE(I)=RHF(NTHE,NOP,CM,HN,OI,SAE)
800   WRITE(6,25)SAE,AE(I)
900   RETURN
      END
C*********************************************************************
C***                                                                ***
```

```
C***                          COMMON FUNCTIONS                          ***
C***                                                                    ***
C************************************************************************
C>>>------------------------------------------------------------------<<<
C>>>                                                                  <<<
C>>>                          PERMUTATION                             <<<
C>>>                                                                  <<<
C>>>------------------------------------------------------------------<<<
      DOUBLE PRECISION FUNCTION PER(M,N)
      IMPLICIT REAL*8 (A-H,O-Z)
      PER=1.D0
      IF ( M .LT. N ) GOTO 200
      IF ( (M .EQ. 0) .OR. (N .EQ. 0) ) GOTO 900
      GOTO 300
200   WRITE(6,201)
201   FORMAT(1X,'ERROR in PERMUTATION function')
      STOP
300   M1=M-N+1
      DO 310 I=M1,M
      PER=PER*I
      IF ( PER .GE. 1.D70) GOTO 200
310   CONTINUE
900   RETURN
      END
C>>>------------------------------------------------------------------<<<
C>>>                                                                  <<<
C>>>                RADIATION INTEGRAL FUNCTION                       <<<
C>>>                                                                  <<<
C>>>          1983 - Chang and Rhee                                   <<<
C>>>                                                                  <<<
C>>>------------------------------------------------------------------<<<
      DOUBLE PRECISION FUNCTION RIF(M,A,X)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION Y(10)
1     FORMAT(1X,'ERROR in RIF function.',//,1X,I10,2E15.4)
      RIF=0.D0
      N=0
100   IF ( ( M .LT. 0 ) .OR. ( A .LT. 0.D0 ) ) GOTO 200
      IF ( M .GT. 9 ) GOTO 200
      IF ( X ) 200,400,300
200   WRITE(6,1) M,A,X
      STOP
300   M1=M+1
      DO 310 I1=1,M1
         I=I1-1
310   Y(I+1)=PER(M,I)
320   N=N+1
      SUM=0.D0
      DO 340 I1=1,M1
         I=I1-1
340   SUM=SUM+Y(I+1)*X**(M-I)/(A+N)**(I+1)
      SUM=SUM*DEXP(-(A+N)*X)
      RIF=RIF+SUM
      IF ( DABS(SUM)-.1D-10 ) 900,900,320
400   N=.5D6**(1.D0/(M+1))-A
```

```
      SUM=0.D0
      DO 420 I=1,N
420   SUM=SUM+1.D0/(A+I)**(M+1)
      RIF=PER(M,M)*(SUM+.5D0*(1.D0/(A+N+1)**M+1.D0/(A+N)**M)/M)
900   RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>            ERROR (PROBABILITY INTEGRAL) FUNCTION                  <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      DOUBLE PRECISION FUNCTION ERRF(X)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR2/CFRE(40),ERFC,ERFCL
      Y=DABS(X)
      IF ( Y .GT. 1.D-15 ) GOTO 200
      ERRF=X
      ERFC=1.D0
      ERFCL=-X-X*X/2.D0
      IF ( Y .LE. .99D-15 ) GOTO 900
      ERRF1=ERRF
200   IF ( Y .GE. 2.35D0 ) GOTO 400
      TERM=2.D0*X/PIST
      ERRF=TERM
      A=0.D0
300   A=A+1.D0
      TERM=-TERM*X*X*(2.D0*A-1.D0)/A/(2.D0*A+1.D0)
      ERRF=ERRF+TERM
      IF (DABS(TERM) .GT. .1D-10 ) GOTO 300
      IF ( Y .GE. 1.D-15 ) GOTO 320
      ERRF=(ERRF*(1.D0-Y*1.D15)+ERRF1*(Y*1.D15-.99D0))*1.D2
320   ERFC=X/Y-ERRF
      ERFCL=DLOG(DABS(ERFC))
      IF ( Y .LE. 2.34D0 ) GOTO 900
      ERRF1=ERRF
400   B=X*X-.5D0
      IF ( Y .GT. 8.D0 ) GOTO 800
      TERM=DEXP(-X*X)/X/PIST
      ERFC=TERM
      IB=B
      DO 600 IA=2,IB
         IF ( DABS(TERM) .LT. 1.D-7) GOTO 700
         TERM=-TERM*(2*IA-3)*.5D0/X/X
600   ERFC=ERFC+TERM
700   ERRF=X/Y-ERFC
      IF ( Y .GE. 2.35D0 ) GOTO 720
      ERRF=(ERRF*(2.35D0-Y)+ERRF1*(Y-2.34D0))*1.D2
720   ERFCL=DLOG(DABS(ERFC))
      IF ( Y .LE. 7.99D0 ) GOTO 900
      ERFC1=ERFC
800   ERRF=Y/X
      ERFCL=-X*X-DLOG(PIST)
      IB=X*X-.5D0
      TERM=1.D0/X
```

```
      SUM=TERM
      DO 820 I=2,IB
         IF ( DABS(TERM) .LT. .1D-10 ) GOTO 840
         TERM=TERM*(2*I-3)*.5D0/X/X
820   SUM=SUM+TERM
840   ERFCL=ERFCL+DLOG(DABS(SUM))
      ERFC=1.D-75
      IF ( DABS(ERFCL) .LT. .1727D3 ) ERFC=DEXP(ERFCL)
      ERFC=Y/X*ERFC
      IF ( Y .GE. 8.D0 ) GOTO 900
      ERFC=(ERFC*(8.D0-Y)+ERFC1*(Y-7.99D0))*1.D2
900   RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>              COEFFICIENTS OF FRE EXPANSION                        <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE ICFRE(NTERMS)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR2/CFRE(40),ERFC,ERFCL
      DIMENSION G(2,41)
      G(1,1)=PIST*.5D0
      DO 300 N=1,NTERMS
         A=2.D0*N-3.D0
         N1=N+1
       G(1,N1)=0.D0
         DO 100 I=1,N1
            G(2,I)=G(1,I)
100      CONTINUE
110      IF (N-1) 900,210,120
120      G(1,N)=4.D0*A*G(2,N-1)/(A+2.D0)*PI/4.D0
         G(1,1)=(G(2,2)+A*G(2,1))/(N-1)/(A+2.D0)*PI/4.D0
130      IF (N-2) 210,210,140
140      N2=N-1
         DO 200 I=2,N2
            G(1,I)=G(2,I+1)*I*(2*I-1)
            G(1,I)=(G(1,I)+(2.D0*(2.D0*A+1.D0)*(I-1)+A)*G(2,I))/N2
200      G(1,I)=(G(1,I)/(A+2.D0)+4.D0*A*G(2,I-1)/(A+2.D0))*PI/4.D0
210      CFRE(N)=G(1,1)
300   CONTINUE
900   RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                    INVERSE ERROR FUNCTION                         <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      DOUBLE PRECISION FUNCTION FRE(Y,YC,YL)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR2/CFRE(40),ERFC,ERFCL
      FRE=0.D0
      A=0.D0
```

```
      X=DABS(Y)
      XC=DABS(YC)
      IF ( X .GT. 1.D0 ) GOTO 150
      IF ( X .LE. .9D0 ) GOTO 200
      IF ( X .LE. .99953D0) GOTO 300
      IF ( XC .GE. 1.D-75 ) GOTO 400
      FRE=.262828D2
      GOTO 900
150   WRITE(6,151)
151   FORMAT(1X,'ERROR in FRE function.')
      STOP
200   A=X
      FRE=FRE+A*CFRE(1)
210   DO 230 I=2,40
         A=A*X*X
         FRE=FRE+A*CFRE(I)
         IF ( A*CFRE(I) .LT. 1.D-7 ) GOTO 900
230   CONTINUE
240   GOTO 900
300   DO 320 I=1,100
         A=PIST*.5D0*DEXP(FRE*FRE)*(X-ERRF(FRE))
         FRE=FRE+A
         IF ( DABS(A) .LT. 1.D-7 ) GOTO 900
320   CONTINUE
      GOTO 900
400   FRE=2.D0
      DLPIST=DLOG(PIST)
      DLXC=DLOG(XC)
      IF ( XC .LE. 1.D-75 ) DLXC=YL
      DO 500 J=1,20
         IF ( A .LT. FRE*FRE-.5D0 ) A=FRE*FRE-.5D0
         TERM=1.D0/FRE
         SUM=TERM
         IA=A
         DO 430 I=2,IA
            TERM=-TERM*(2*I-3)*.5D0/FRE/FRE
            SUM=SUM+TERM
            IF ( DABS(TERM/SUM) .LT. .1D-10 ) GOTO 440
430      CONTINUE
440      FRE1=FRE
         TERM=DLOG(SUM)-DLXC-DLPIST
         IF ( TERM .LT. 0.D0 ) GOTO 900
         FRE=DSQRT(TERM)
         IF (DABS(FRE-FRE1) .LE. .1D-10 ) GOTO 900
500   CONTINUE
900   FRE=Y/X*FRE
      RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                  GAUSS NUMERICAL INTEGRATION                      <<<
C>>>                                                                   <<<
C>>>                                                                   <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
```

```
      DOUBLE PRECISION FUNCTION GNI(XU,XL,Y)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION C(5),Y(5)
      DATA C/.11846344250,.2393143352D0,.28444444440,.2393143352D0,
     +       .11846344250/
      GNI=0.D0
      DO 100 I=1,5
100   GNI=GNI+C(I)*Y(I)
      GNI=GNI*(XU-XL)
      RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>            X positions of 5 points GNI                            <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE GNIX(XU,XL,X)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION U(5),X(5)
      DATA U/-.90617984600,-.5384693102D0,0.D0,.5384693102D0,
     +       .90617984600/
      DO 100 I=1,5
100   X(I)=.5D0*(XU+XL+(XU-XL)*U(I))
      RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>         Adiabatic Flame Temperature coefficients                  <<<
C>>>                                                                   <<<
C>>>                                                                   <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE AFTC(P,CM,HN,OI)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR7/REFL,REFTP,REFQ,REFW,REFWL,CVLWL
      COMMON /BLKRC/TA,TB,TC
1     FORMAT(' ERROR in AFTC - P = ',E12.4,' atm.   Fuel = ',3E12.4)
      IF ( (CM .GE. 0.D0) .AND. (HN .GE. 0.D0) .AND. (OI .GE. 0.D0)
     +     .AND. (P .GE. 0.D0) ) GOTO 100
90    WRITE(6,1)P,CM,HN,OI
      STOP
100   IF ( OI .LE. 0.D0 ) GOTO 200
C>>>
C>>>   Alcohol family
C>>>
      IF ( (CM .LT. .19D1) .OR. (CM .GT. .81D1) ) GOTO 90
      A1=.21535D4+.602D2*DLOG(CM-.151D1)
      A2=-.5D0+.52D1*DLOG(CM+.11D0)
      B1=.641D0-.3D-1*DLOG(CM+.34D1)
      B2=.4D-3+.66D-2*DLOG(CM+.2D-1)
      C1=.193D0-.41D-1*DLOG(CM+.35D1)
      C2=-.2D-3+.66D-2*DLOG(CM+.9D-1)
      GOTO 900
C>>>
C>>>   Hydrogen
```

```
C>>>
200   IF ( CM .GT. 0.D0 ) GOTO 300
      A1=.24122D4
      A2=.179D2
      B1=.473D0
      B2=.21D-1
      C1=.217D-1
      C2=.191D-1
      GOTO 900
C>>>
C>>>   Acetylene
C>>>
300   IF ( (CM .NE. 2.D0) .AND. (HN .NE. 2.D0) ) GOTO 400
      A1=.25629D4
      A2=.423D2
      B1=.39D0
      B2=.426D-1
      C1=-.819D-1
      C2=.379D-1
      GOTO 900
C>>>
C>>>   Paraffin family
C>>>
400   IF ( HN .LT. 2.D0*CM+1.D0 ) GOTO 500
      IF ( CM .GT. .161D2 ) GOTO 90
      A1=.2295D4+.95D1*DLOG(CM-.99D0)
      A2=.132D2+.7D0*DLOG(CM-.97D0)
      B1=.544D0-.19D-2*DLOG(CM-.99D0)
      B2=.18D-1+.9D-3*DLOG(CM-.96D0)
      C1=.7D-1-.3D-2*DLOG(CM-.98D0)
      C2=.169D-1+.8D-3*DLOG(CM-.97D0)
      GOTO 900
500   IF ( HN .LT. 2.D0*CM-1.D0) GOTO 600
C>>>
C>>>   Olefin family
C>>>
      IF ( (CM .LT. .19D1) .OR. (CM .GT. .161D2) ) GOTO 90
      A1=.2377D4-.179D2*DLOG(CM-.185D1)
      A2=.199D2-.14D1*DLOG(CM-.189D1)
      B1=.512D0-.85D-2*DLOG(CM-.189D1)
      B2=.25D-1-.14D-2*DLOG(CM-.186D1)
      C1=.35D-1+.83D-2*DLOG(CM-.189D1)
      C2=.23D-1-.13D-2*DLOG(CM-.186D1)
      GOTO 900
C>>>
C>>>   Aromatic family
C>>>
600   IF ( (CM .LT. .59D1) .OR. (CM .GT. .221D2) ) GOTO 90
      A1=.2378D4-.153D2*DLOG(CM-.536D1)
      A2=.21D2-.16D1*DLOG(CM-.529D1)
      B1=.518D0+.6D-2*DLOG(CM-.551D1)
      B2=.27D-1-.2D-2*DLOG(CM-.524D1)
      C1=.34D-1+.8D-2*DLOG(CM-.538D1)
      C2=.25D-1-.16D-2*DLOG(CM-.527D1)
C>>>
```

```
C>>>   Estimated AFT Formulas
C>>>
900    X=DLOG(P)
       TA=(A1+A2*X)/REFTP
       TB=B1+B2*X
       TC=C1+C2*X
       RETURN
       END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>          Adiabatic Flame Temperature estimate                     <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
       DOUBLE PRECISION FUNCTION AFT(FA)
       IMPLICIT REAL*8 (A-H,O-Z)
       COMMON /BLKRC/TA,TB,TC
       IF ( FA .GE. 0.D0 ) GOTO 100
       WRITE(6,1)FA
1      FORMAT(' Error in AFT : F/A=',E12.3)
       STOP
100    IF ( (FA .LE. .4D0) .OR. (FA .GE. 1.6D0) ) GOTO 200
       FALOG=DLOG(FA)
       IF ( FA .GT. 1.D0) FALOG=DLOG(2.D0-FA)
       AFT=TA*(1.D0+TB*FALOG+TC*FALOG*FALOG)
       RETURN
200    AFT=.25D0
       RETURN
       END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>              Mean distribution properties                         <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
       SUBROUTINE XMEAN(FVM,FAM,XHM,XCM)
       IMPLICIT REAL*8 (A-H,O-Z)
       COMMON /BLKR1/PI,PIST,PI4
       COMMON /BLKR3/FVF,FVA,FVB,FVC,FAF,FAA,FAB,FAC,XHF,XHA,XHB,XHC,
      +              XCF,XCA,XCB,XCC
       COMMON /BLKR4/RHODN,PHIDN,ZDN,THEIN,OMES,RNZ,VS,NFP
       COMMON /BLKR5/RCB,ZCB,ZCC,ZCCB,RP
       COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
       DIMENSION RX(5),WX(5),ZX(5)
       DIMENSION FVI(5),FVJ(5),FVK(5),FAI(5),FAJ(5),FAK(5)
       DIMENSION XHI(5),XHJ(5),XHK(5),XCI(5),XCJ(5),XCK(5)
       VOL=PI*(ZCC*RP*RP+ZCB*RCB*RCB)/NFP
       FVM=0.D0
       FAM=0.D0
       XHM=0.D0
       XCM=0.D0
       DO 20 L=1,5
          FVI(L)=0.D0
          FVJ(L)=0.D0
          FVK(L)=0.D0
          FAI(L)=0.D0
          FAJ(L)=0.D0
```

```
          FAK(L)=0.D0
          XHI(L)=0.D0
          XHJ(L)=0.D0
          XHK(L)=0.D0
          XCI(L)=0.D0
          XCJ(L)=0.D0
20      XCK(L)=0.D0
        RU=RP
        WU=PI/NFP
        ZU=0.D0
        ZL=-ZCC
40      CALL GNIX(ZU,ZL,ZX)
        DO 300 I=1,5
          Z=ZX(I)
          CALL GNIX(WU,0.D0,WX)
          DO 200 J=1,5
            W=WX(J)
            SW=DSIN(W)
            CW=DCOS(W)
            CALL GNIX(RU,0.D0,RX)
            DO 100 K=1,5
              R=DSQRT(RX(K))
              X=R*CTHEIN*CW-Z*STHEIN
              Y=R*SW
              RN=DSQRT(X*X+Y*Y)
              WN=DATAN2(Y,X)
              ZN=R*STHEIN*CW+Z*CTHEIN
              G=-(FVA*RN+FVB*WN*WN+FVC*ZN*ZN)
              FVK(K)=FVF*DEXP(G)
              G=-(FAA*RN+FAB*WN*WN+FAC*ZN*ZN)
              FAK(K)=FAF*DEXP(G)
              G=-(XHA*RN+XHB*WN*WN+XHC*ZN*ZN)
              XHK(K)=XHF*DEXP(G)
              G=-(XCA*RN+XCB*WN*WN+XCC*ZN*ZN)
100         XCK(K)=XCF*DEXP(G)
            FVJ(J)=GNI(ZU,ZL,FVK)
            FAJ(J)=GNI(ZU,ZL,FAK)
            XHJ(J)=GNI(ZU,ZL,XHK)
200       XCJ(J)=GNI(ZU,ZL,XCK)
          FVI(I)=GNI(WU,WL,FVJ)
          FAI(I)=GNI(WU,WL,FAJ)
          XHI(I)=GNI(WU,WL,XHJ)
300     XCI(I)=GNI(WU,WL,XCJ)
        FVM=FVM+GNI(RU,0.D0,FVI)/VOL
        FAM=FAM+GNI(RU,0.D0,FAI)/VOL
        XHM=XHM+GNI(RU,0.D0,XHI)/VOL
400     XCM=XCM+GNI(RU,0.D0,XCI)/VOL
        IF ( DABS(ZL+ZCCB) .LT. .1D-10 ) GOTO 900
        ZU=-ZCC
        ZL=-ZCCB
        RU=RCB*RCB
        GOTO 40
900     RETURN
        END
C*******************************************************************************
```

```
C***                                                                  ***
C***                  RADIATION HEAT FLUX                             ***
C***                                                                  ***
C***                                                                  ***
C***                                                                  ***
C**********************************************************************
      DOUBLE PRECISION FUNCTION RHF(NTHE,NOP,CM,HN,OI,SAE)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR4/RHODN,PHIDN,ZDN,THEIN,OMES,RNZ,VS,NFP
      COMMON /BLKR8/OL,P,PE,T,TO,W
      COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
      COMMON /BLKRC/TA,TB,TC
      COMMON /BLKRE/THEN,ZETN,STHEN,CTHEN,SZETN,CZETN
      COMMON /BLKRF/QRS(10),RHFRNR,QRSNR(10),RHFRP,QRSP(10)
      DIMENSION CTHEX(5),ZETX(5),SAE(10)
      DIMENSION QTZ(5),QSTZ(5,10),QT(5),GQS(10),QST(5,10)
      DIMENSION QTZNR(5),QSTZNR(5,10),QTNR(5),GQSNR(10),QSTNR(5,10)
      DIMENSION QTZP(5),QSTZP(5,10),QTP(5),GQSP(10),QSTP(5,10)
      DIMENSION SRHF(10),SRHFNR(10),SRHFP(10)
1     FORMAT(1X,'QN   = ',6E10.3,/,18X,5E10.3,/,1X,'QSW  = ',6E10.3,
     +/,18X,5E10.3,/,1X,'QSP  = ',6E10.3,/,18X,5E10.3)
      RHF=0.D0
      RHFNR=0.D0
      RHFP=0.D0
      DO 100 I=1,10
         SRHF(I)=0.D0
         SRHFNR(I)=0.D0
100   SRHFP(I)=0.D0
C>>>
C>>>  Compute flame temperature parameters.
C>>>
      CALL AFTC(P,CM,HN,OI)
      IF ( DABS(PHIDN) .LE. PI/NFP ) GOTO 120
      JFP=DABS(PHIDN)*NFP/2.D0/PI+.5D0
      PHIFP=PI*2.D0*JFP/NFP
      IF ( PHIDN .LT. 0.D0 ) PHIFP=-PHIFP
      PHIDN=PHIDN+PHIFP
C>>>
C>>>  Compute heat flux in specified solid angle.
C>>>
120   CTHEL=+1.D0
      DCTHE=-2.D0/NTHE
C>>>
C>>>  Integrate heat flux in sub-intervals of THE domain.
C>>>
      DO 600 J=1,NTHE
         CTHEU=CTHEL+DCTHE
         CALL GNIX(CTHEU,CTHEL,CTHEX)
         DO 500 K=1,5
            QT(K)=0.D0
            QTNR(K)=0.D0
            QTP(K)=0.D0
            DO 140 K1=1,10
               QST(K,K1)=0.D0
```

```
                  QSTNR(K,K1)=0.D0
140            QSTP(K,K1)=0.D0
               ZETL=-PI
               CTHEN=CTHEX(K)
               STHEN=DSQRT(1.D0-CTHEN*CTHEN)
               IF ( STHEN .LE. 0.D0 ) GOTO 500
               THEN=DATAN2(STHEN,CTHEN)
               NZET=1+STHEN/.25D0
               IF ( (RHODN .LT. 1.D0) .AND. (STHEN .GT. .75D0) ) NZET=2
               IF ( RHODN .LT. .1D-10 ) NZET=NZET+NZET
               DZET=2.D0*PI/NZET
C>>>
C>>>  Integrate heat flux in sub-intervals of ZET domain.
C>>>
               DO 400 L=1,NZET
                  ZETU=ZETL+DZET
                  IF ( DABS(ZETU) .LT. .1D-10 ) ZETU=0.D0
                  CALL GNIX(ZETU,ZETL,ZETX)
                  DO 300 M=1,5
                     ZETN=ZETX(M)
                     IF ( DABS(ZETN) .LE. .1D-10 ) ZETN=0.D0
                     SZETN=DSIN(ZETN)
                     CZETN=DCOS(ZETN)
                     DTHEN=THEN*.18D3/PI
                     DZETN=ZETN*.18D3/PI
                     PDN=PHIDN
                     QTZ(M)=RHFR(NOP,PDN,REOP)
                     QTZNR(M)=RHFRNR
                     QTZP(M)=RHFRP
                     DO 200 M1=1,10
                        QSTZ(M,M1)=QRS(M1)
                        QSTZNR(M,M1)=QRSNR(M1)
200                  QSTZP(M,M1)=QRSP(M1)
300               CONTINUE
                  IF ( REOP .LT. .1D-10 ) GOTO 400
                  QT(K)=QT(K)+GNI(ZETU,ZETL,QTZ)/PI
                  QTNR(K)=QTNR(K)+GNI(ZETU,ZETL,QTZNR)/PI
                  QTP(K)=QTP(K)+GNI(ZETU,ZETL,QTZP)/PI
                  DO 320 K1=1,10
                     DO 310 K2=1,5
                        GQS(K2)=QSTZ(K2,K1)
                        GQSNR(K2)=QSTZNR(K2,K1)
310                  GQSP(K2)=QSTZP(K2,K1)
                     QST(K,K1)=QST(K,K1)+GNI(ZETU,ZETL,GQS)/PI
                     QSTNR(K,K1)=QSTNR(K,K1)+GNI(ZETU,ZETL,GQSNR)/PI
320               QSTP(K,K1)=QSTP(K,K1)+GNI(ZETU,ZETL,GQSP)/PI
400            ZETL=ZETU
500         CONTINUE
            RHF=RHF-GNI(CTHEU,CTHEL,QT)
            RHFNR=RHFNR-GNI(CTHEU,CTHEL,QTNR)
            RHFP=RHFP-GNI(CTHEU,CTHEL,QTP)
            DO 520 L1=1,10
               DO 510 L2=1,5
                  GQS(L2)=QST(L2,L1)
                  GQSNR(L2)=QSTNR(L2,L1)
```

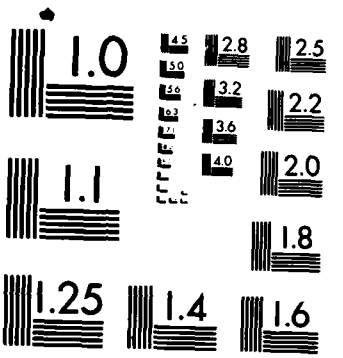
```
510           GQSP(L2)=QSTP(L2,L1)
              SRHF(L1)=SRHF(L1)-GNI(CTHEU,CTHEL,GQS)
              SRHFNR(L1)=SRHFNR(L1)-GNI(CTHEU,CTHEL,GQSNR)
520        SRHFP(L1)=SRHFP(L1)-GNI(CTHEU,CTHEL,GQSP)
600     CTHEL=CTHEU
        WRITE(6,1)RHF,SRHF,RHFNR,SRHFNR,RHFP,SRHFP
        RIF1=1.D0
        DO 700 I=1,10
           X=.7D0*I
           RIF2=RIF(3,0.D0,X)*.15D2/PI4
           IF ( I .GE. 10 ) RIF2=0.D0
           SAE(I)=SRHF(I)/(RIF1-RIF2)
700     RIF1=RIF2
        RETURN
        END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>                    RANGE of an OPTICAL PATH                     <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
        SUBROUTINE ROP(REOP,TDS,TES,ODS,OES,N)
        IMPLICIT REAL*8 (A-H,O-Z)
        COMMON /BLKR1/PI,PIST,PI4
        COMMON /BLKR4/RHODN,PHIDN,ZDN,THEIN,OMES,RNZ,VS,NFP
        COMMON /BLKR5/RCB,ZCB,ZCC,ZCCB,RP
        COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
        COMMON /BLKRD/TSCH,TSCW,TSP,TSB,ES
        COMMON /BLKRE/THEN,ZETN,STHEN,CTHEN,SZETN,CZETN
        REOP=0.D0
        TDS=0.D0
        TES=0.D0
        ODS=0.D0
        OES=0.D0
        PHIN=0.D0
        A=DCOS(PHIDN+ZETN)
C>>>
C>>>  Check if detector locates on combustion surface and
C>>>           optical ray shoots into combustion chamber.
C>>>
        IF ( (-ZDN-ZCC .GE. -.1D-10) .AND. (DABS(ZCC) .GT. .1D-10) )
     +    GOTO 200
        IF ( (DABS(ZCC) .LT. .1D-10) .AND. ( RHODN .GT. RCB) ) GOTO 200
        IF ( (DABS(ZCC) .LT. .1D-10) .AND. (RHODN .LE. RCB) ) GOTO 210
        IF ( (ZDN .GT. .1D-10) .OR. (RHODN-RP .GT. .1D-10) ) GOTO 900
        IF ( (DABS(ZDN) .LT. .1D-10) .AND. (THEN .GE. .5D0*PI) ) GOTO 900
        IF ( (A .GE. 0.D0) .AND. (DABS(RHODN-RP) .LT. .1D-10) ) GOTO 900
        IF ( (DABS(ZDN+ZCC) .LT. .1D-10) .AND. (RCB-RHODN .GT. SAMLL) )
     +    GOTO 900
        IF ( (DABS(ZDN+ZCC) .LT. .1D-10) .AND. (THEN .LT. .5D0*PI) )
     +  GOTO 900
        GOTO 210
200     IF ( (-ZDN-ZCCB .GT. .1D-10) .OR. (RHODN-RCB .GT. .1D-10) )
     +  GOTO 900
        IF ( (DABS(ZDN+ZCCB) .LT. .1D-10) .AND. (THEN .LE. .5D0*PI) )
     +  GOTO 900
```

```
      IF ( (DABS(RHODN-RCB) .LT. .1D-10) .AND. (A .GE. 0.D0) )
     +  GOTO 900
C>>>
C>>>  Determine temperature and orientation of detector surface.
C>>>
210   N=1
      IF ( -ZDN .LT. .1D-10 ) GOTO 220
      N=2
      IF ( ZDN+ZCC .GT. .1D-10 ) GOTO 220
      N=3
      IF ( DABS(ZDN+ZCC) .LT. .1D-10 ) GOTO 220
      N=4
      IF ( ZDN+ZCCB .GT. .1D-10 ) GOTO 220
      N=5
220   CALL TOCCS(N,PHIDN,TDS,ODS)
C>>>
C>>>  Find the end point of optical path.
C>>>
300   IF ( THEN .GT. .1D-10 ) GOTO 320
      IF ( RHODN .LE. RCB ) GOTO 310
      N=3
      GOTO 330
310   N=5
      GOTO 340
320   IF ( DABS(THEN-PI) .GT. .1D-10 ) GOTO 400
      N=1
      IF ( RHODN .LT. RCB ) GOTO 340
330   REOP=ZCC
      GOTO 800
340   REOP=ZCCB
      GOTO 800
400   IF ( RHODN .GT. .1D-10 ) GOTO 410
      R1=RP/STHEN
      R21=RCB/STHEN
      R22=0.D0
      GOTO 450
410   B1=A*A+RP*RP/RHODN/RHODN-1.D0
      B2=A*A+RCB*RCB/RHODN/RHODN-1.D0
      R1=RHODN*(-A+DSQRT(B1))/STHEN
      IF ( B2 .GE. 0.D0 ) GOTO 420
      R21=0.D0
      R22=0.D0
      GOTO 450
420   IF ( RHODN .GT. RCB ) GOTO 430
      R22=0.D0
      GOTO 440
430   R22=RHODN*(-A-DSQRT(B2))/STHEN
440   R21=RHODN*(-A+DSQRT(B2))/STHEN
450   Z1=-R1*CTHEN+ZDN
      Z21=-R21*CTHEN+ZDN
      Z22=-R22*CTHEN+ZDN
      IF ( -ZDN-ZCC .GT. .1D-10 ) GOTO 600
460   IF ( -Z1 .GT. 0.D0 ) GOTO 520
510   REOP=-ZDN/CTHEN
      N=1
```

AD-A161 433 A THERMODYNAMIC SYSTEM ANALYSIS MODEL OF A DIESEL ENGINE(U) RUTGERS - THE STATE UNIV NEW BRUNSWICK N J DEPT OF MECHANICAL K T RHEE ET AL 16 OCT 85 2/2

UNCLASSIFIED ARO-21770 4-EG DAAG29-84-K-0158 F/G 21/7 NL

END



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
      GOTO 800
520   IF ( -Z1 .GT. ZCC ) GOTO 540
530   REOP=R1
      N=2
      GOTO 700
540   IF ( (-Z21 .GT. ZCC) .AND. (-Z22 .LT. ZCC) ) GOTO 550
      REOP=(ZCC+ZDN)/CTHEN
      N=3
      GOTO 800
550   IF ( -Z21 .GT. ZCCB ) GOTO 580
570   REOP=R21
      N=4
      GOTO 700
580   REOP=(ZCCB+ZDN)/CTHEN
      N=5
      GOTO 800
600   IF ( -Z21 .GT. ZCCB) GOTO 580
620   IF ( -Z21 .GT. ZCC ) GOTO 570
640   IF ( -Z1 .LT. 0.D0 ) GOTO 510
660   GOTO 530
700   IF ( DABS(RHODN) .GT. .1D-10 ) GOTO 750
720   PHIN=-ZETN
      GOTO 800
750   XEOP=REOP*STHEN/RHODN
      SPDN=DSIN(PDN)-XEOP*SZETN
      CPDN=DCOS(PDN)+XEOP*CZETN
      PHIN=DATAN2(SPDN,CPDN)
800   CALL TOCCS(N,PHIN,TES,OES)
      REOP=DABS(REOP)
900   RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>          Orientation of Combustion Chamber Surface              <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE TOCCS (N,PHIN,TS,OS)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKRD/TSCH,TSCW,TSP,TSB,ES
      COMMON /BLKRE/THEN,ZETN,STHEN,CTHEN,SZETN,CZETN
      IF ( N-2 ) 100,200,300
100   TS=TSCH
      GOTO 700
200   TS=TSCW
      GOTO 800
300   IF ( N-4 ) 400,500,600
400   TS=TSP
      GOTO 700
500   TS=TSB
      GOTO 800
600   TS=TSB
700   OS=DABS(CTHEN)
      RETURN
800   OS=DABS(STHEN*DCOS(ZETN+PHIN))
      RETURN
```

```
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                RHF along an OPTICAL PATH                          <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      DOUBLE PRECISION FUNCTION RHFR(NOP,PDN,REOP)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR2/CFRE(40),ERFC,ERFCL
      COMMON /BLKR3/FVF,FVA,FVB,FVC,FAF,FAA,FAB,FAC,XHF,XHA,XHB,XHC,
     +              XCF,XCA,XCB,XCC
      COMMON /BLKR7/REFL,REFTP,REFQ,REFW,REFWL,CVLWL
      COMMON /BLKR8/OL,P,PE,T,TO,W
      COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
      COMMON /BLKRB/THE,ZET
      COMMON /BLKRC/TA,TB,TC
      COMMON /BLKRD/TSCH,TSCW,TSP,TSB,ES
      COMMON /BLKRF/QRS(10),RHFRNR,QRSNR(10),RHFRP,QRSP(10)
      DIMENSION CKO(10),QDS(10),QES(10),QRY(5),TAU(5),TAUR(10)
      DIMENSION RS(5),PHIS(5)
      RHFR=0.D0
      RHFRP=0.D0
      RHFRNR=0.D0
      NSUB=0
      DO 100 I=1,10
         QRS(I)=0.D0
         QRSNR(I)=0.D0
100   QRSP(I)=0.D0
C>>>
C>>>  Find range of optical path and surface temperature.
C>>>
      CALL ROP(REOP,TDS,TES,ODS,OES,NEOP)
      IF ( REOP .GT. 0.D0 ) GOTO 120
      RETURN
120   DX=0.2D0
      DWN=0.7D0
      R1=0.D0
      R2=REOP
C>>>
C>>>  Compute surface emission power
C>>>
      TES4=TES*TES*TES*TES
      TDS4=TDS*TDS*TDS*TDS
      A=0.D0
      YE1=0.D0
      YD1=0.D0
      EE1=PI4/.15D2
      ED1=PI4/.15D2
      DO 150 I=1,9
         IF ( TES .GT. .1D-10 ) GOTO 130
         QES(I)=0.D0
         GOTO 150
130      YE1=YE1+DWN/TES
         IF ( TDS .GT. .1D-10 ) GOTO 140
```

```
          QDS(I)=0.D0
          GOTO 150
140       YD1=YD1+DWN/TDS
          EE2=RIF(3,0.D0,YE1)
          ED2=RIF(3,0.D0,YD1)
          QES(I)=TES4*.15D2/PI4*(EE1-EE2)*OES
          QDS(I)=TDS4*.15D2/PI4*(ED1-ED2)*ODS
          EE1=EE2
150     ED1=ED2
        QES(10)=TES4*.15D2/PI4*EE2*OES
        QDS(10)=TDS4*.15D2/PI4*ED2*ODS
160     DO 170 I=1,10
          CKO(I)=0.D0
          IF ( I .GT. 5 ) GOTO 170
          QRY(I)=0.D0
          TAU(I)=0.D0
170     TAUR(I)=0.D0
        RI=0.D0
        CALL CTDL(THE,ZET)
        STHE=DSIN(THE)
        IF ( RHOD .LE. 0.D0 ) GOTO 180
        NSUB=REOP*STHE/RHOD/DX
180     IF ( NSUB .LT. NOP ) NSUB=NOP
        IF ( NSUB .LE. 50 ) GOTO 200
        NSUB=50
        R2=DX*RHOD*NSUB/STHE
200     DR=(R2-R1)/NSUB
        RI=R1+DR*.5D0
        OL=DR*REFL*CVLWL/REFWL
C>>>
C>>>  Heat flux integration along optical path.
C>>>
        DO 500 I=1,NSUB
          CALL CTDL(THE,ZET)
210       SPHID=DSIN(PHID)
          CPHID=DCOS(PHID)
          IF ( DABS(RHOD) .LT. .1D-10 ) RHOD=0.D0
          IF ( DABS(ZD) .LT. .1D-10 ) ZD=0.D0
C>>>
C>>>  Coordinate transformations
C>>>
          CALL CT(FVF,FVA,FVB,FVC,FVDL,RCFV,RWFV)
          CALL CT(FAF,FAA,FAB,FAC,FADL,RCFA,RWFA)
          CALL CT(XHF,XHA,XHB,XHC,XHDL,RCXH,RWXH)
          CALL CT(XCF,XCA,XCB,XCC,XCDL,RCXC,RWXC)
C>>>
C>>>  Compute combined volume absorptance.
C>>>
          ZFA=(RI-RCFA)/RWFA
          ZFA=FADL-ZFA*ZFA
          IF ( DABS(ZFA) .GT. .1727D3 ) ZFA=ZFA/DABS(ZFA)*.1727D3
          FA=DEXP(ZFA)
          IF ( FA .LT. .2D0 ) GOTO 500
          T=AFT(FA)
          ZFV=(RI-RCFV)/RWFV
```

```
      ZXH=(RI-RCXH)/RWXH
      ZXC=(RI-RCXC)/RWXC
      ZXH=XHDL-ZXH*ZXH
      ZXC=XCDL-ZXC*ZXC
      ZFV=FVDL-ZFV*ZFV
      IF ( DABS(ZFV) .GT. .1727D3 ) ZFV=ZFV/DABS(ZFV)*.1727D3
      FV=0.D0
      IF ( DABS(FVF) .GT. 0.D0 ) FV=DEXP(ZFV)
      IF ( DABS(ZXH) .GT. .1727D3 ) ZXH=ZXH/DABS(ZXH)*.1727D3
      XH=0.D0
      IF ( DABS(XHF) .GT. 0.D0 ) XH=DEXP(ZXH)
      IF ( DABS(ZXC) .GT. .1727D3 ) ZXC=ZXC/DABS(ZXC)*.1727D3
      XC=0.D0
      IF ( DABS(XCF) .GT. 0.D0 ) XC=DEXP(ZXC)
      CALL CVA(FV,XH,XC,CKO,FVDL,XHDL,XCDL)
      IF ( FVF .NE. 0.D0 ) GOTO 212
      RWFV=RWXH
      RCFV=RCXH
212   Z2=(RI+DR*.5D0-RCFV)/RWFV
      Z1=(RI-DR*.5D0-RCFV)/RWFV
214   WN1=0.D0
      ERFZ1=ERRF(Z1)
      ERFCZ1=ERFC
      ERFLZ1=ERFCL
      ERFZ2=ERRF(Z2)
      ERFCZ2=ERFC
      ERFLZ2=ERFCL
C>>>
C>>>  integrate along optical path at each spectral band.
C>>>
      DO 400 J=1,10
         IF ( (DABS(FVDL) .GT. .1727D3) .OR. (DABS(XHDL) .GT.
     +      .1727D3) .OR. (DABS(XCDL) .GT. .1727D3) ) GOTO 220
         TAUW=.5D0*PIST*CKO(J)*RWFV*REFL*CVLWL/REFWL
         TAUC=TAUR(J)-TAUW*ERFZ1
         TAURU=TAUW*ERFZ2+TAUC
         IF ( DABS(ERFCZ1) .GT. 1.D-15 ) GOTO 230
         TAUC=TAUR(J)+TAUW*ERFCZ1
         TAURU=TAUC-TAUW*ERFCZ2
         GOTO 230
220      TAUW1=CKO(J)+ERFLZ1
         IF ( DABS(TAUW1) .GT. .1727D3 ) TAUW1=DABS(TAUW1)/
     +        TAUW1*.1727D3
         TAUW1=DEXP(TAUW1)*.5D0*PIST*RWFV*REFL*CVLWL/REFWL
         TAUW2=CKO(J)+ERFLZ2
         IF ( DABS(TAUW2) .GT. .1727D3 ) TAUW2=DABS(TAUW2)/
     +        TAUW2*.1727D3
         TAUW2=DEXP(TAUW2)*.5D0*PIST*RWFV*REFL*CVLWL/REFWL
         TAUC=TAUR(J)+TAUW1*DABS(Z1)/Z1
         TAURU=TAUC-TAUW2*DABS(Z2)/Z2
230      IF ( TAURU .LE. TAUR(J) ) GOTO 400
         CALL GNIX(TAURU,TAUR(J),TAU)
         DO 300 K=1,5
            IF ( J .GT. 1 ) GOTO 260
            IF ( (DABS(FVDL) .GT. .1727D3) .OR. (DABS(XHDL) .GT.
```

```
     +          .1727D3) .OR. (DABS(XCDL) .GT. .1727D3) ) GOTO 240
                TAUS=(TAU(K)-TAUC)/TAUW
                TAUSC=TAUS/DABS(TAUS)-TAUS
                IF ( DABS(ERFCZ1) .GT. 1.D-15 ) GOTO 250
                TAUD=TAUC-TAU(K)
                TAUSL=DLOG(DABS(TAUD))-DLOG(TAUW)
                TAUSC=1.D-75
                IF ( DABS(TAUSL) .LT. .1727D3 ) TAUSC=DEXP(TAUSL)
                TAUSC=TAUD/DABS(TAUD)*TAUSC
                TAUS=TAUD/DABS(TAUD)*.999999D0
                GOTO 250
240             YY=TAUC-TAU(K)
                TAUS=YY/DABS(YY)*.9999999D0
                TAUSC=1.D-75
                XX=.5D0*PIST*RWFV*REFL*CVLWL/REFWL
                YY=DABS(YY)
                IF ( YY .LE. 0.D0 ) YY=1.D-75
                TAUSL=DLOG(YY)-CK0(J)-DLOG(XX)
250             RS(K)=FRE(TAUS,TAUSC,TAUSL)*RWFV+RCFV
                IF ( RWFA .GT. 1.D70 ) RCFA=RS(K)
260             ZFA=(RS(K)-RCFA)/RWFA
                ZFA=FADL-ZFA*ZFA
                IF ( DABS(ZFA) .GT. .1727D3 ) ZFA=ZFA/DABS(ZFA)*.1727D3
                FA=DEXP(ZFA)
                IF ( FA .GT. .2D0 ) GOTO 280
                QRY(K)=0.D0
                GOTO 300
280             T=AFT(FA)
                A=T*TAU(K)
                Y1=WN1/T
                Y2=(WN1+DWN)/T
                RIF2=0.D0
                IF ( J .LT. 10 ) RIF2=RIF(4,A,Y2)
                RIF1=RIF(4,A,Y1)
                QRY(K)=T*T*T*T*T*(RIF1-RIF2)*.15D2/PI4
300           CONTINUE
              QRS(J)=QRS(J)+GNI(TAURU,TAUR(J),QRY)
              TAUR(J)=TAURU
400         WN1=WN1+DWN
500       RI=RI+DR
          IF ( R2 .GE. REOP ) GOTO 520
          R1=R2
          R2=REOP
          NSUB=NOP
          GOTO 200
C>>>
C>>>   Net radiation heat flux on detection surface. (mean reflection)
C>>>
520       RFL=1.D0-ES
          DO 600 I=1,10
             X=.35D0+.7D0*(I-1)
             QRSP(I)=QRS(I)*ODS
             RHFRP=RHFRP+QRSP(I)
             QRSNR(I)=ES*ODS*QRS(I)-QDS(I)
             RHFRNR=RHFRNR+QRSNR(I)
```

```
      EXT=0.D0
      IF ( TAUR(I) .LT. 1.D2 ) EXT=DEXP(-TAUR(I)*X)
      BES=(QES(I)+RFL*OES*QRS(I)+RFL*OES*EXT*(QDS(I)+RFL*ODS
     +     *QRS(I)))/(1.D0-RFL*RFL*OES*ODS*EXT*EXT)
      QRS(I)=ES*ODS*(QRS(I)+BES*EXT)-QDS(I)
      TAUR(I)=EXT
600   RHFR=RHFR+QRS(I)
      RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>                 COMBINED VOLUMETRIC ABSORPTANCE                 <<<
C>>>                                                                 <<<
C>>>            OL - dimensionless optical length (ref:6u)           <<<
C>>>            T - dimensionless temperature (ref:2400K)            <<<
C>>>            P - dimensionless pressure (ref:1atm)                <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE CVA(FV,XH2O,XCO2,CKO,FVDL,XHDL,XCDL)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR8/OL,P,PE,T,TO,W
      DIMENSION CKO(10),VU(11),VL(11)
1     FORMAT('  *** CVA error : (fv,XH2O,XCO2) = ',3E10.3)
2     FORMAT('  *** CVA error : (I-EMIS-CKO) = ',I5,2E15.3)
      IF ( (FV .LE. 1.D0) .AND. (XH2O .LE. 1.D0) .AND.
     +     (XCO2 .LE. 1.D0) ) GOTO 100
      WRITE(6,1) FV,XH2O,XCO2
      STOP
100   CALL GAS(XH2O,XCO2,VU,VL)
      IF ( VU(1) .LT. .1D-10 ) VU(1)=0.D0
      J=1
      NWN=10
      DWN=7.D0/NWN
      WN=0.D0
      DO 500 I=1,NWN
         A=0.D0
150      IF ( (I .GE. NWN) .AND. (J .LE. 11) ) GOTO 200
         IF ( (VL(J) .GE. WN+DWN) .OR. (J .GT. 11) ) GOTO 400
200      C1=WN
         IF ( VL(J) .GT. WN ) C1=VL(J)
         C2=VU(J)
         IF ( VU(J) .LT. WN+DWN ) GOTO 300
         A=A+WN+DWN-C1
         VL(J)=WN+DWN
         GOTO 400
300      A=A+C2-C1
         J=J+1
         GOTO 150
400      WNC=WN+.5D0*DWN
         WL=1.D0/WNC
         EMIS=A/DWN
         IF ( EMIS .GE. 0.D0 ) GOTO 440
420      WRITE(6,2) I,EMIS,CKO(I)
         STOP
440      IF ( EMIS .GE. 1.D0-1.D-15 ) EMIS=1.D0-1.D-15
```

```
          CKO(I)=SOOTA(WL,FV)-DLOG(1.D0-EMIS)/WNC/OL
          IF ( CKO(I) .LT. 0.D0 ) GOTO 420
          IF ( CKO(I) .EQ. 0.D0 ) GOTO 500
          IF ( FV .NE. 0.D0 ) GOTO 450
          IF ( DABS(XHDL) .LE. .1727D3 ) GOTO 445
          CKO(I)=DLOG(CKO(I))+XHDL-DLOG(XH2O)
          GOTO 500
445       CKO(I)=CKO(I)*DEXP(XHDL)/XH2O
          GOTO 500
450       IF ( (DABS(FVDL) .LE. .1727D3) .AND. (DABS(XHDL) .LE.
     +    .1727D3) .AND. (DABS(XCDL) .LE. .1727D3) ) GOTO 460
          CKO(I)=DLOG(CKO(I))+FVDL-DLOG(FV)
          GOTO 500
460       CKO(I)=CKO(I)*DEXP(FVDL)/FV
500     WN=WN+DWN
        RETURN
        END
C*******************************************************************************
C***                                                                          ***
C***                        SOOT RADIATION                                    ***
C***                                                                          ***
C***                                                                          ***
C***                                                                          ***
C*******************************************************************************
C>>>-------------------------------------------------------------------------<<<
C>>>                                                                         <<<
C>>>            MEAN SPECTRAL SOOT ABSORPTIVITY                              <<<
C>>>                                                                         <<<
C>>>         1966 - Howarth, Forster and Thring                              <<<
C>>>         1969 - Dalzell and Sarofim                                      <<<
C>>>         1981 - Lee and Tien                                             <<<
C>>>                                                                         <<<
C>>>         WL - dimensionless wave length ( ref:6u )                       <<<
C>>>         FV - soot volume fraction                                       <<<
C>>>         SOOTA - mean soot absorptance                                   <<<
C>>>                                                                         <<<
C>>>-------------------------------------------------------------------------<<<
        DOUBLE PRECISION FUNCTION SOOTA(WL,FV)
        IMPLICIT REAL*8 (A-H,O-Z)
        COMMON /BLKR1/PI,PIST,PI4
        IF ( WL .GE. 0.D0 ) GOTO 200
100     WRITE(6,101)
101     FORMAT(1X,'ERROR in SOOTA function.')
        STOP
200     CALL SOC(WL,X,Y)
        SOOTA=18.D0*PI*Y*FV/((X+2.D0)**2+Y*Y)
        RETURN
        END
C>>>-------------------------------------------------------------------------<<<
C>>>                                                                         <<<
C>>>               OPTICAL CONSTANTS OF SOOT                                 <<<
C>>>                                                                         <<<
C>>>          1981 - Lee and Tien                                            <<<
C>>>                                                                         <<<
C>>>        - dimensionless operation                                        <<<
```

```
C>>>        - electronic dispersion function                              <<<
C>>>        - dispersion constants, F, G & WN (Lee & Tien)                <<<
C>>>                                                                      <<<
C>>>----------------------------------------------------------------------<<<
      SUBROUTINE SOC(WL,X,Y)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR6/F(3),G(3),WN(3),VLGT
      X=1.DO
      Y=0.DO
      W=2.DO*PI*VLGT/WL
      DO 200 I=1,3
         A=WN(I)*WN(I)-W*W
         B=A*A+W*W*G(I)*G(I)
         IF ( DABS(B) .LT. 1.D-75 ) GOTO 900
100      X=X+F(I)*A/B
         Y=Y+F(I)*G(I)*W/B
200   CONTINUE
900   RETURN
      END
C*************************************************************************
C***                                                                   ***
C***                        GAS RADIATION                              ***
C***                                                                   ***
C***          1972 - Edwards and Balakrishnan                          ***
C***          1983 - Chang and Rhee                                    ***
C***                                                                   ***
C***          X??? - molar fraction of gas ???                         ***
C***          VU - dimensionless upper bound of gas bands              ***
C***          VL - dimensionless lower bound of gas bands              ***
C***                                                                   ***
C*************************************************************************
      SUBROUTINE GAS(XH2O,XCO2,VU,VL)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AA1(5),AA2(6),VU(11),VL(11)
1     FORMAT(' XH2O = ',E12.4,'  XCO2 = ',E12.4)
      IF( ( XH2O .GE. 0.DO ) .OR. ( XCO2 .GE. 0.DO ) ) GOTO 100
      WRITE(6,1) XH2O,XCO2
      STOP
100   VU(2)=.160D4
      VU(3)=.376D4
      VU(4)=.535D4
      VU(5)=.725D4
      VU(6)=.667D3
      VU(7)=.960D3
      VU(8)=.106D4
      VU(10)=.366D4
      VU(11)=.520D4
      CALL AH2O(XH2O,AA1)
      CALL ACO2(XCO2,AA2)
      VU(1)=AA1(1)*.5DO
      VU(9)=.2410D4-AA2(4)*.5DO
      DO 200 I=1,5
         VU(I)=VU(I)+AA1(I)*.5DO
200   VL(I)=VU(I)-AA1(I)
```

```
      DO 300 I=1,6
         VU(I+5)=VU(I+5)+AA2(I)*.5D0
300   VL(I+5)=VU(I+5)-AA2(I)
      DO 400 I=1,10
         I1=I+1
         DO 400 J=I1,11
            IF( VL(I) .LE. VL(J) ) GOTO 400
            TEMP=VL(I)
            TEMP1=VU(I)
            VL(I)=VL(J)
            VU(I)=VU(J)
            VL(J)=TEMP
            VU(J)=TEMP1
400   CONTINUE
      DO 500 I=1,10
         IF( VU(I) .LE. VL(I+1) ) GOTO 500
         IF( VU(I) .LT. VU(I+1) ) GOTO 420
         VU(I+1)=VU(I)
420      VU(I)=VL(I+1)
500   CONTINUE
      DO 600 I=1,11
         VU(I)=VU(I)*.6D-3
600   VL(I)=VL(I)*.6D-3
      RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>              BAND ABSORTANCE of WATER                           <<<
C>>>                                                                 <<<
C>>>         1973 - Edwards and Balakrishnan                         <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE AH2O(X,AA)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AA(5),B(3),ND(3),NG(3),V(3)
      COMMON /BLKR8/OL,P,PE,T,T0,W
      DATA NG/1,1,1/,V/3.652D3,1.595D3,3.756D3/
      IF( (X .GT. 0.D0) .AND. (T .GT. 0.D0) ) GOTO 200
      DO 100 I=1,5
100   AA(I)=0.D0
      RETURN
200   DST=DSQRT(T/T0)
      PE=P+P*X*(.86D1/DST-.5D0)
      W=P*X*OL/T/1.824D3
      B(1)=.52D4*DEXP(-.176D2/DST)
      B(2)=.14311D0
      B(3)=.284D2
      ND(1)=0
      ND(2)=0
      ND(3)=0
      CALL A1(V,NG,B,ND,AA(1))
      B(1)=.412D2
      B(2)=.9427D-1
      B(3)=.564D2
      ND(2)=1
```

```
      CALL A1(V,NG,B,ND,AA(2))
      B(1)=.19D0
      B(2)=.13219D0
      B(3)=.6D2
      ND(2)=2
      CALL PSIPHI(T0,V,NG,ND,PSI0,PHI0)
      CALL PSIPHI(T,V,NG,ND,PSI,PHI)
      T1=B(1)*PSI/PSI0
      T4=B(2)*PHI/PHI0
      B(1)=.23D1
      ND(1)=1
      ND(2)=0
      CALL PSIPHI(T0,V,NG,ND,PSI0,PHI0)
      CALL PSIPHI(T,V,NG,ND,PSI,PHI)
      T2=B(1)*PSI/PSI0
      T5=B(2)*PHI/PHI0
      B(1)=.224D2
      ND(1)=0
      ND(3)=1
      CALL PSIPHI(T0,V,NG,ND,PSI0,PHI0)
      CALL PSIPHI(T,V,NG,ND,PSI,PHI)
      T3=B(1)*PSI/PSI0
      T6=B(2)*PHI/PHI0
      C1=T1+T2+T3
      C3=B(3)*DST
      C2=2.D0*DSQRT(C3)*(DSQRT(T1*T4)+DSQRT(T2*T5)+DSQRT(T3*T6))
      CALL BANDA(C1,C2,C3,AA(3))
      B(1)=3.D0
      B(2)=.8169D-1
      B(3)=.431D2
      ND(2)=1
      CALL A1(V,NG,B,ND,AA(4))
      B(1)=.25D1
      B(2)=.11628D0
      B(3)=.32D2
      ND(1)=1
      ND(2)=0
      CALL A1(V,NG,B,ND,AA(5))
      RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>          PSI and PHI functions of GAS EMISSION                    <<<
C>>>                                                                   <<<
C>>>          1968 - Weiner and Edwards                                <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE PSIPHI(T,V,NG,ND,PSI,PHI)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION V(3),NG(3),U(3),ND(3),NV(3)
      COMMON /BLKR7/REFL,REFTP,REFQ,REFW,REFWL,CVLWL
      IF ( (ND(1) .NE. 0) .OR. (ND(2) .NE. 0)
     +.OR. (ND(3) .NE. 0) ) GOTO 100
      PSI=1.D0
      PHI=1.D0/DSQRT(T)
```

```
      RETURN
100   M=3
      UD=0.D0
      XD=0.D0
      XY=0.D0
      YN=0.D0
      DO 400 K=1,M
         U(K)=V(K)*REFWL*1.D-4/T
         NV(K)=0
         IF ( ND(K) .LT. 0 ) NV(K)=IABS(ND(K))
         NDK=IABS(ND(K))
         Y1=0.D0
200      X=DEXP(-U(K)*NV(K))/PER(NG(K)-1,NG(K)-1)
            X1=X*PER(NV(K)+NG(K)+NDK-1,NG(K)+NDK-1)
            X2=X*PER(NV(K)+NG(K)-1,NG(K)-1)
            IF( X1 .LT. 1.D-10 ) GOTO 300
            XY=XY+X1
            XD=XD+X2
            Y1=Y1+DSQRT(X1)
            NV(K)=NV(K)+1
         IF( NV(K) .LT. 100 ) GOTO 200
300      YN=YN+Y1*Y1
         UD=UD-U(K)*ND(K)
400   CONTINUE
      PSI=(1.D0-DEXP(UD))*XY/XD
      PHI=YN/XY/DSQRT(T)
      RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>            . APPROXIMATION to GAS BAND ABSORPTANCE              <<<
C>>>                                                                 <<<
C>>>          1964 - Edwards and Menard                              <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE BANDA(C1,C2,C3,A)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR8/OL,P,PE,T,T0,W
1     FORMAT(T20,'***** ERROR IN BANDA *****',/,T20,5E12.4)
      IF( (C1 .LT. 0.D0) .OR. (C2 .LT. 0.D0) .OR. (C3 .LT. 0.D0) )
     +    GOTO 200
      IF( W*PE ) 200,100,300
100   A=0.D0
      RETURN
200   WRITE(6,1)C1,C2,C3,PE,W
      STOP
300   E=C2*C2*PE/(4.D0*C1*C3)
      IF ( E .GT. 1.D0 ) GOTO 400
      TEST1=E*C3
      TEST2=C3*(2.D0-E)
      A=C1*W
      IF( A .LE. TEST1 ) GOTO 900
      A=C2*DSQRT(W*PE)-E*C3
      IF( A .LE. TEST2 ) GOTO 900
      X=E*C1*W/C3
```

```
      A=C3*(DLOG(X)+2.D0-E)
      GOTO 900
400   TEST=C3
      A=C1*W
      IF( A .LE. TEST ) GOTO 900
      X=C1*W/C3
      A=C3*(DLOG(X)+1.D0)
900   RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>              GAS BAND ABSORPTANCE (regular bands)                 <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE A1(V,NG,B,ND,A)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION B(3),ND(3),V(3),NG(3)
      COMMON /BLKR8/OL,P,PE,T,T0,W
      CALL PSIPHI(T0,V,NG,ND,PSI0,PHI0)
      CALL PSIPHI(T,V,NG,ND,PSI,PHI)
      C3=B(3)*DSQRT(T/T0)
      C1=B(1)*PSI/PSI0
      C2=2.D0*DSQRT(C1*C3*B(2)*PHI/PHI0)
      CALL BANDA(C1,C2,C3,A)
      RETURN
      END
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>        BAND ABSORPTANCES of CARBON DIOXIDE                        <<<
C>>>                                                                   <<<
C>>>          1973 - Edwards and Balakrishnan                          <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SUBROUTINE ACO2(X,AA)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AA(6),B(3),ND(3),NG(3),V(3)
      COMMON /BLKR8/OL,P,PE,T,T0,W
      DATA NG/1,2,1/,V/1.351D3,6.67D2,2.396D3/
      DO 100 I=1,6
100   AA(I)=0.D0
      W=P*X*OL/T/7.462D2
      IF ( W .LE. 0.D0 ) RETURN
      PE=(P+P*X*0.3D0)**0.7D0
      B(1)=.19D2
      B(2)=.6157D-1
      B(3)=.127D2
      ND(1)=0
      ND(2)=1
      ND(3)=0
      CALL A1(V,NG,B,ND,AA(1))
      PE=(P+P*X*0.3D0)**0.8D0
      B(1)=0.36D0
      B(2)=.4017D-1
      B(3)=.134D2
      ND(1)=-1
```

```
      ND(2)=0
      ND(3)=1
      CALL A1(V,NG,B,ND,AA(2))
      B(1)=.24D0
      B(2)=.11888D0
      B(3)=.101D2
      CALL A1(V,NG,B,ND,AA(3))
      B(1)=.11D3
      B(2)=.24723D0
      B(3)=.112D2
      ND(1)=0
      CALL A1(V,NG,B,ND,AA(4))
      PE=(P+P*X*0.3D0)**0.65D0
      B(1)=4.D0
      B(2)=0.13341
      B(3)=23.5
      ND(1)=1
      CALL A1(V,NG,B,ND,AA(5))
      B(1)=.66D-1
      B(2)=.39305D0
      B(3)=.345D2
      ND(1)=2
      CALL A1(V,NG,B,ND,AA(6))
      RETURN
      END
C*******************************************************************************
C***                                                                          ***
C***                    Coordinate Transformation                             ***
C***                                                                          ***
C***           Fuel-plume  <--->  Optical path                                ***
C***                                                                          ***
C*******************************************************************************
      SUBROUTINE CT(FF,A,B,C,FDL,RC,RW)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR4/RHODN,PHIDN,ZDN,THEIN,OMES,RNZ,VS,NFP
      COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
      COMMON /BLKRB/THE,ZET
1     FORMAT(3X,'*** ERROR in CT - (THE:ZET:RI:A1:B1:C1) = ',/,27X,
     +       6E12.3)
      STHE=DSIN(THE)
      CTHE=DCOS(THE)
      SZET=DSIN(ZET)
      CZET=DCOS(ZET)
      SPHID=DSIN(PHID)
      CPHID=DCOS(PHID)
      IF ( FF .EQ. 0.D0 ) GOTO 20
      IF ( (A .NE. 0.D0) .OR. (B .NE. 0.D0) .OR. (C .NE. 0.D0) )
     +      GOTO 40
20    FDL=-1.D0
      IF ( DABS(FF) .GT. 0.D0 ) FDL=DLOG(FF)
      RC=RI
      RW=1.D70
      RETURN
40    ALP=.85D-1/RNZ
      PHIS1=(OMES*CTHEIN/VS)*(1.D0+ALP*.5D0)
```

```
      IF ( DABS(RHOD) .GT. .1D-10 ) GOTO 100
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>      Radial component (RHO term) -                                <<<
C>>>              I.  RHOD = 0                                         <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      SR=1.D0
      XI=RI
      RHOE=RI*STHE
      RHOA=RHOE
      RHOB=STHE
      RHOC=0.D0
      RHO0=0.D0
      RHO1=STHE
      RHO2=0.D0
      RHO=RHOE
      GOTO 230
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>              II. RHOD <> 0                                        <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
100   SR=STHE/RHOD
      XI=RI*SR
      ARHO=DCOS(PHID+ZET)
      IF ( XI .LT. 1.D1 ) GOTO 120
      RHO0=RHOD*ARHO
      RHO1=RHOD
      RHO2=0.D0
      GOTO 200
120   FA=DSQRT(1.D0+2.D0*ARHO*XI+XI*XI)
      RHOA=RHOD*FA
      RHOB=RHOD*(ARHO+XI)/FA
      RHOC=RHOD*(FA*FA-(ARHO+XI)*(ARHO+XI))/FA/FA/FA
      RHO0=RHOA-RHOB*XI+RHOC*XI*XI*.5D0
      RHO1=RHOB-RHOC*XI
      RHO2=RHOC*.5D0
      RHO=RHO0+RHO1*XI+RHO2*XI*XI
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>          Angular component (PHI term) -                           <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
200   IF ( THE .NE. 0.D0 ) GOTO 220
      RHOE=RHOD
      GOTO 230
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>              EXACT TRANSFORMATION                                 <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
220   RHOE=RHOD*DSQRT(1.D0+2.D0*ARHO*XI+XI*XI)
230   X1=CPHID+XI*CZET
      X2=SPHID-XI*SZET
```

```
      IF ( (X1 .EQ. 0.D0) .AND. (X2 .EQ. 0.D0) ) X1=1.D0
      PHIE=DATAN2(X2,X1)
      ZE=ZD-RI*CTHE
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>         Approximated Transformation - swirl effect                <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
240   PHISA=PHIS1*RHOE*(1.D0+ALP*RHOE*.5D0)/(1.D0+ALP*.5D0)
      PHISB=PHIS1*(1.D0+ALP*RHOE)/(1.D0+ALP*.5D0)*RHOB
      PHISC=PHIS1*ALP/(1.D0+ALP*.5D0)*RHOB*RHOB+PHISB*RHOC
      IF ( (RHOD .GT. .1D-10) .AND. ( XI .LT. 1.D1) ) GOTO 250
      PHIA=-ZET
      PHIB=0.D0
      PHIC=0.D0
      GOTO 300
250   X3=DSIN(PHID+ZET)
      IF ( DABS(X3) .GT. .1D-10 ) GOTO 280
      PHIB=0.D0
      PHIC=0.D0
      IF ( RHO .LT. 0.D0 ) GOTO 260
         PHIA=PHID
         GOTO 300
260   PHIA=-PHID
         RHO=-RHO
         GOTO 300
280   PHIA=PHIE
      IF ( DABS(X1) .GT. .1D-10 ) GOTO 290
      PHIB=-CZET*CZET/X3
      PHIC=0.D0
      GOTO 300
290   FA=X2/X1
      FB=-X3/X1/X1
      FC=-2.D0*FB*CZET/X1
      G=1.D0+FA*FA
      PHIB=FB/G
      PHIC=(-2.D0*FA*FB*FB+G*FC)/G/G
300   PSIA=PHIA-PHISA
      PSIB=PHIB-PHISB
      PSIC=PHIC-PHISC
320   BPHIA=PSIA*PSIA
      BPHIB=2.D0*PSIA*PSIB
      BPHIC=2.D0*PSIA*PSIC+2.D0*PSIB*PSIB
      BPHI0=BPHIA-BPHIB*XI+BPHIC*XI*XI*.5D0
      BPHI1=BPHIB-BPHIC*XI
      BPHI2=BPHIC*.5D0
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>         Coefficients - Approximated Transformation                <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
400   A1=A*RHO0+B*BPHI0+C*ZD*ZD
      B1=-(A*RHO1+B*BPHI1)*SR+2.D0*C*ZD*CTHE
      C1=(A*RHO2+B*BPHI2)*SR*SR+C*CTHE*CTHE
      IF ( C1 .GT. 0.D0 ) GOTO 420
```

```
      COMMON /BLKRE/THEN,ZETN,STHEN,CTHEN,SZETN,CZETN
      ALP=.85D-1/RNZ
      XI=RI*STHEN
      RHO1=XI*XI+2.D0*DCOS(PHIDN-ZETN)*XI*RHODN+RHODN*RHODN
      RHO1=DSQRT(RHO1)
      Y=RHODN*DSIN(PHIDN)-XI*DSIN(ZETN)
      X=RHODN*DCOS(PHIDN)+XI*DCOS(ZETN)
      PHI1=-ZETN
      IF ( (DABS(X) .GT. .1D-10) .OR. (DABS(Y) .GT. .1D-10) )
     +PHI1=DATAN2(Y,X)
      Z1=ZDN-RI*CTHEN
      JFP=DABS(PHI1)*NFP/2.D0/PI+.5D0
      PHIFP=PI*2.D0*JFP/NFP
      IF ( PHI1 .LT. 0.D0 ) PHIFP=-PHIFP
      ZETFP=-PHIFP
      CALL CTIFP(ZETFP,THEIN,THEN,ZETN,THE,ZET)
      PDN=PHIDN-PHIFP
      X1=RHODN*DCOS(PDN)
      Y1=RHODN*DSIN(PDN)
      X2=X1*CTHEIN-ZDN*STHEIN
      Y2=Y1
      ZD=X1*STHEIN+ZDN*CTHEIN
      RHOD=DSQRT(X2*X2+Y2*Y2)
      PHID=PDN
      IF ( (DABS(Y2) .GT. .1D-10) .OR. (DABS(X2) .GT. .1D-10) )
     +   PHID=DATAN2(Y2,X2)
      RETURN
      END
C*******************************************************************************
C***                                                                         ***
C***              2-D TRANSIENT CONDUCTION                                   ***
C***            - Finite difference approximation in space                   ***
C***                and successive differenciation in time                   ***
C***                                                                         ***
C***                          (CONFU.FOR)                                    ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C***                                                                         ***
C*******************************************************************************
        SUBROUTINE MATRIC
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKC1/XC(60),YC(60),C(60),CK(60)
      COMMON /BLKC2/A(60,60),B(60,60)
      COMMON /BLKC3/D(60),UBD(60),U0(60),UB(60)
      COMMON /BLKC4/REFT,REFDT,REFC,REFK,REFLC,NPT,NU,NBC,NBCT,NLP
      COMMON /BLKC5/L1(80),L2(80),L3(80),I1(80),I2(80),I3(80),
     1              J1(80),J2(80),J3(80)
      COMMON /BLKC6/REFQC,REFA,REFTK,REFU
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                    WRITING FORMATS                                <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
```

```
      FDL=-.172703
      RC=0.D0
      RW=1.D0
      RETURN
420   IF ( C1 .LT. .1D-10 ) C1=.1D-10
      X=A1-B1*B1*.25D0/C1
      FDL=DLOG(FF)-X
      RC=B1/C1*.5D0
      RW=1.D0/DSQRT(C1)
900   RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>          Spherical Coordinate Transformation                    <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE CTIFP(ZETFP,THEIN,THEO,ZETO,THE,ZET)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION EX(3),EY(3),EZ(3),PT(3)
      STHEIN=DSIN(THEIN)
      CTHEIN=DCOS(THEIN)
      CZETFP=DCOS(ZETFP)
      SZETFP=DSIN(ZETFP)
      EX(1)=CTHEIN*CZETFP
      EX(2)=CTHEIN*SZETFP
      EX(3)=STHEIN
      EY(1)=-SZETFP
      EY(2)=CZETFP
      EY(3)=0.D0
      EZ(1)=-STHEIN*CZETFP
      EZ(2)=-STHEIN*SZETFP
      EZ(3)=CTHEIN
      PT(1)=DSIN(THEO)*DCOS(ZETO)
      PT(2)=DSIN(THEO)*DSIN(ZETO)
      PT(3)=DCOS(THEO)
      CTHE=PT(1)*EZ(1)+PT(2)*EZ(2)+PT(3)*EZ(3)
      STHE=DSQRT(1.D0-CTHE*CTHE)
      THE=DATAN2(STHE,CTHE)
      X=PT(1)*EX(1)+PT(2)*EX(2)+PT(3)*EX(3)
      Y=PT(1)*EY(1)+PT(2)*EY(2)+PT(3)*EY(3)
      ZET=ZETO
      IF ( (DABS(Y) .GT. .1D-10) .OR. (DABS(X) .GT. .1D-10) )
     +   ZET=DATAN2(Y,X)
      RETURN
      END
C>>>-----------------------------------------------------------------<<<
C>>>                                                                 <<<
C>>>      Coordinate Transformation of Detector's Location           <<<
C>>>                                                                 <<<
C>>>-----------------------------------------------------------------<<<
      SUBROUTINE CTDL(THE,ZET)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /BLKR1/PI,PIST,PI4
      COMMON /BLKR4/RHODN,PHIDN,ZDN,THEIN,OMES,RNZ,VS,NFP
      COMMON /BLKRA/RHOD,PHID,ZD,RI,STHEIN,CTHEIN
```

```
10    FORMAT(2F7.1,3E10.3,5I5)
11    FORMAT(2F10.4,2E10.3,F10.4)
12    FORMAT(16I5)
13    FORMAT(E10.3)
14    FORMAT(10F7.1)
15    FORMAT(8E10.3,/,4E10.3)
16    FORMAT(4E10.3)
20    FORMAT(19H reference temp. = ,11X,F6.1,1HK,/,13H temp. span =,
     117X,F6.1,1HK,/,14H capacitance =,16X,F10.5, 12HJ/cm/cm/cm/K,/,
     1 14H conductance =,16X,F10.5, 6Hv/cm/K,/, 8Hlength =,21X,F8.3,
     13H cm,/,20H # of nodal points =,11X,I3,/,13H # of loops =,18X,
     113,/,15H # of unknows =,16X,I3,/,12H # of BC's =,19X,I3,/,
     118H # of temp. BC's =,13X,I3,///)
21    FORMAT(1X,15I5)
22    FORMAT(11(1X,F5.1))
23    FORMAT(14(1X,F5.1))
24    FORMAT(1X,12F9.4)
25    FORMAT(1X,12E9.2)
      WRITE(6,20) REFT,REFDT,REFC,REFK,REFLC,NPT,NLP,NU,NBC,NBCT
C>>>-------------------------------------------------------------------<<<
C>>>                        NORMALIZATION                              <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      REFQC=REFK*REFDT/REFLC
      REFA=REFK/REFC
      REFTK=REFLC*REFLC/REFA
      REFU=REFC*REFDT/REFTK
      WRITE(6,11) XC(3),YC(3),C(3),CK(3),U0(3)
      DO 100 N=1,NPT
         C(N)=C(N)/REFC
         CK(N)=CK(N)/REFK
         U0(N)=(U0(N)-REFT)/REFDT
         XC(N)=XC(N)/REFLC
         YC(N)=YC(N)/REFLC
100   WRITE(6,11) XC(N),YC(N),C(N),CK(N),U0(N)
C>>>-------------------------------------------------------------------<<<
C>>>                                                                   <<<
C>>>                        MATRIX FORMULATION                         <<<
C>>>                                                                   <<<
C>>>-------------------------------------------------------------------<<<
      DO 300 I=1,NLP
         WRITE(6,21) I,L1(I),I1(I),J1(I),L2(I),I2(I),J2(I),
     1L3(I),I3(I),J3(I)
         R12=DSQRT((XC(L1(I))-XC(L2(I)))**2+(YC(L1(I))-YC(L2(I)))**2)
         R13=DSQRT((XC(L1(I))-XC(L3(I)))**2+(YC(L1(I))-YC(L3(I)))**2)
         A12=(XC(L3(I))*(YC(L2(I))-YC(L1(I)))-YC(L3(I))*(XC(L2(I))
     1-XC(L1(I)))+XC(L2(I))*YC(L1(I))
     1      -XC(L1(I))*YC(L2(I)))*.5D0/R12
         A12=DABS(A12)
         A13=(XC(L2(I))*(YC(L3(I))-YC(L1(I)))-YC(L2(I))*(XC(L3(I))
     1-XC(L1(I)))+XC(L3(I))*YC(L1(I))
     1      -XC(L1(I))*YC(L3(I)))*.5D0/R13
         A13=DABS(A13)
         V2=A12*R12*.25D0
         V3=A13*R13*.25D0
```

```
      V1=A12*R12*.5D0
      CD12=(CK(L1(I))+CK(L2(I)))*.5D0*A12/R12
      CD13=(CK(L1(I))+CK(L3(I)))*.5D0*A13/R13
    IF ( (I1(I) .GT. 0) .AND. (I2(I) .GT. 0) .AND. (I3(I) .GT. 0) )
   1 GOTO 200
      IF ( (I2(I) .LE. 0) .OR. (I3(I) .LE. 0) ) GOTO 120
         A(L1(I),L1(I))=A(L1(I),L1(I))-CD12-CD13
         B(L1(I),I2(I))=B(L1(I),I2(I))+CD12
         B(L1(I),I3(I))=B(L1(I),I3(I))+CD13
         D(L1(I))=D(L1(I))+C(L1(I))*V1
         GOTO 200
120   IF ( (I1(I) .LE. 0) .OR. (I3(I) .LE. 0) ) GOTO 130
         A(L2(I),L2(I))=A(L2(I),L2(I))-CD12
         B(L2(I),I1(I))=B(L2(I),I1(I))+CD12
         D(L2(I))=D(L2(I))+C(L2(I))*V2
        GOTO 200
130   IF ( (I1(I) .LE. 0) .OR. (I2(I) .LE. 0) ) GOTO 140
         A(L3(I),L3(I))=A(L3(I),L3(I))-CD13
         B(L3(I),I1(I))=B(L3(I),I1(I))+CD13
         D(L3(I))=D(L3(I))+C(L3(I))*V3
         GOTO 200
140   IF ( I3(I) .LE. 0 ) GOTO 150
         A(L1(I),L1(I))=A(L1(I),L1(I))-CD12-CD13
         A(L1(I),L2(I))=A(L1(I),L2(I))+CD12
         A(L2(I),L2(I))=A(L2(I),L2(I))-CD12
         A(L2(I),L1(I))=A(L2(I),L1(I))+CD12
         B(L1(I),I3(I))=B(L1(I),I3(I))+CD13
         D(L1(I))=D(L1(I))+C(L1(I))*V1
         D(L2(I))=D(L2(I))+C(L2(I))*V2
         GOTO 200
150   IF ( I2(I) .LE. 0 ) GOTO 160
         A(L1(I),L1(I))=A(L1(I),L1(I))-CD12-CD13
         A(L1(I),L3(I))=A(L1(I),L3(I))+CD13
         A(L3(I),L3(I))=A(L3(I),L3(I))-CD13
         A(L3(I),L1(I))=A(L3(I),L1(I))+CD13
         B(L1(I),I2(I))=B(L1(I),I2(I))+CD12
         D(L1(I))=D(L1(I))+C(L1(I))*V1
         D(L3(I))=D(L3(I))+C(L3(I))*V3
         GOTO 200
160   IF ( I1(I) .LE. 0 ) GOTO 170
         A(L2(I),L2(I))=A(L2(I),L2(I))-CD12
         A(L3(I),L3(I))=A(L3(I),L3(I))-CD13
         B(L2(I),I1(I))=B(L2(I),I1(I))+CD12
         B(L3(I),I1(I))=B(L3(I),I1(I))+CD13
         D(L2(I))=D(L2(I))+C(L2(I))*V2
         D(L3(I))=D(L3(I))+C(L3(I))*V3
         GOTO 200
170      A(L1(I),L1(I))=A(L1(I),L1(I))-CD12-CD13
         A(L1(I),L2(I))=A(L1(I),L2(I))+CD12
         A(L1(I),L3(I))=A(L1(I),L3(I))+CD13
         A(L2(I),L2(I))=A(L2(I),L2(I))-CD12
         A(L2(I),L1(I))=A(L2(I),L1(I))+CD12
         A(L3(I),L3(I))=A(L3(I),L3(I))-CD13
         A(L3(I),L1(I))=A(L3(I),L1(I))+CD13
         D(L1(I))=D(L1(I))+C(L1(I))*V1
```

```
            D(L2(I))=D(L2(I))+C(L2(I))*V2
            D(L3(I))=D(L3(I))+C(L3(I))*V3
200       IF ( I1(I) .GE. 0 ) GOTO 220
            I1(I)=IABS(I1(I))
            IF ( (J1(I) .NE. L2(I)) .AND. (J1(I) .NE. L2(I)+L3(I)) )
     1         GOTO 210
               B(L1(I),I1(I))=B(L1(I),I1(I))+R12*.5D0
210         IF ( (J1(I) .NE. L3(I)) .AND. (J1(I) .NE. L2(I)+L3(I)) )
     1         GOTO 220
               B(L1(I),I1(I))=B(L1(I),I1(I))+R13*.5D0
220       IF ( I2(I) .GE. 0 ) GOTO 240
            I2(I)=IABS(I2(I))
            IF ( (J2(I) .NE. L3(I)) .AND. (J2(I) .NE. L3(I)+L1(I)) )
     1         GOTO 230
               B(L2(I),I2(I))=B(L2(I),I2(I))+R23*.5D0
230         IF ( (J2(I) .NE. L1(I)) .AND. (J2(I) .NE. L3(I)+L1(I)) )
     1         GOTO 240
               B(L2(I),I2(I))=B(L2(I),I2(I))+R13*.5D0
240       IF ( I3(I) .GE. 0 ) GOTO 260
            I3(I)=IABS(I3(I))
            IF ( (J3(I) .NE. L1(I)) .AND. (J3(I) .NE. L1(I)+L2(I)) )
     1         GOTO 250
               B(L3(I),I3(I))=B(L3(I),I3(I))+R13*.5D0
250         IF ( (J3(I) .NE. L2(I)) .AND. (J3(I) .NE. L1(I)+L2(I)) )
     1         GOTO 260
               B(L3(I),I3(I))=B(L3(I),I3(I))+R23*.5D0
260    IF ( I .LT. NLP ) GOTO 300
       WRITE(6,22) ((A(K1,K2),K2=1,NU),K1=1,NU)
       WRITE(6,23) ((B(K1,K2),K2=1,NBC),K1=1,NU)
300    CONTINUE
       DO 400 I=1,NU
          DO 320 J=1,NU
320       A(I,J)=A(I,J)/D(I)
          DO 340 J=1,NBC
340       B(I,J)=B(I,J)/D(I)
400    CONTINUE
       WRITE(6,22) ((A(K1,K2),K2=1,NU),K1=1,NU)
       WRITE(6,23) ((B(K1,K2),K2=1,NBC),K1=1,NU)
       RETURN
       END
C*****************************************************************************
C***                                                                       ***
C***                    CONDUCTION HEAT FLUX                               ***
C***                                                                       ***
C*****************************************************************************
       SUBROUTINE COND(UB1,TK0,TK)
       IMPLICIT REAL*8 (A-H,O-Z)
       COMMON /BLKC2/A(60,60),B(60,60)
       COMMON /BLKC3/D(60),UBD(60),U0(60),UB(60)
       COMMON /BLKC4/REFT,REFDT,REFC,REFK,REFLC,NPT,NU,NBC,NBCT,NLP
       COMMON /BLKC6/REFQC,REFA,REFTK,REFU
       DIMENSION UD(60),UD0(60),U(60),UB1(60)
1      FORMAT(1X,12F9.4)
2      FORMAT(3F10.3)
C>>>-------------------------------------------------------------<<<
```

```
C>>>                                                                  <<<
C>>>                  BOUNDARY CONDITIONS                             <<<
C>>>                                                                  <<<
C>>>------------------------------------------------------------------<<<
      TKO=TKO/REFTK
      DO 420 I=1,NBC
         IF ( I .GT. NBCT ) GOTO 410
         UB(I)=(UB(I)-REFT)/REFDT
         GOTO 420
410      UB(I)=UB(I)/REFQC
420   CONTINUE
      TK=TK/REFTK
      DTK=TK-TKO
      TKO=TK
      DO 530 I=1,NBC
         IF ( I .GT. NBCT ) GOTO 510
         UB1(I)=(UB1(I)-REFT)/REFDT
         GOTO 520
510      UB1(I)=UB1(I)/REFQC
520      UBD(I)=UB1(I)-UB(I)
530   UB(I)=UB1(I)
      WRITE(6,1) (UB1(I),I=1,NBC)
      WRITE(6,2) TKO,TK,DTK
C>>>------------------------------------------------------------------<<<
C>>>                                                                  <<<
C>>>                    SERIES EXPANSION                              <<<
C>>>                                                                  <<<
C>>>------------------------------------------------------------------<<<
      DO 620 I=1,NU
         UDO(I)=0.DO
         DO 610 J=1,NU
610      UDO(I)=UDO(I)+A(I,J)*UO(J)
         DO 620 J=1,NBC
620   UDO(I)=UDO(I)+B(I,J)*UB(J)
      DO 630 I=1,NU
         UDO(I)=UDO(I)*DTK
630   U(I)=UO(I)+UDO(I)
      WRITE(6,1) (U(I),I=1,NU)
      DO 650 I=1,NU
         UD(I)=0.DO
         DO 640 J=1,NU
640      UD(I)=UD(I)+A(I,J)*UDO(J)
        DO 650 J=1,NBC
650   UD(I)=UD(I)+B(I,J)*UBD(J)
      DO 700 I=2,50
         TEST=0.DO
         DO 660 J=1,NU
            UD(J)=UD(J)*DTK/I
            TEST=TEST+UD(J)*UD(J)
            UDO(J)=UD(J)
660      U(J)=U(J)+UD(J)
         WRITE(6,1) (U(J),J=1,NU)
         TEST=DSQRT(TEST/NU)
         IF ( TEST .LE. .1D-10 ) GOTO 800
         DO 670 K=1,NU
```

```
 0.0000     0.0000 .350E+001 .392E+000  500.0000
 0.5000     0.0000 .350E+001 .392E+000  500.0000
 1.0000     0.0000 .350E+001 .392E+000  500.0000
 1.5000     0.0000 .350E+001 .392E+000  500.0000
 2.0000     0.0000 .350E+001 .392E+000  500.0000
 2.5000     0.0000 .350E+001 .392E+000  500.0000
 3.0000     0.0000 .350E+001 .392E+000  500.0000
 3.5000     0.0000 .350E+001 .392E+000  500.0000
 4.0000     0.0000 .350E+001 .392E+000  500.0000
 4.5000     0.0000 .350E+001 .392E+000  500.0000
 5.0000     0.0000 .100E+001 .392E+000  500.0000
 1  -15     7     5  -16     1     2   -26     1
 6    0     0     2  -26     0     5   -16     0
 6    0     0     2  -26     0     7     0     0
 3  -27     2     2  -26     3     7     0     0
 7    0     0     3  -27     0     8     0     0
 4  -28     3     3  -27     4     8     0     0
 9  -17     5     5  -16     9    10     0     0
 6    0     0     5  -16     0    10     0     0
10    0     0     6    0     0    11     0     0
 7    0     0     6    0     0    11     0     0
 7    0     0     8    0     0    11     0     0
12    0     0     8    0     0    11     0     0
13  -18     9     9  -17    13    14     0     0
10    0     0     9  -17     0    14     0     0
10    0     0    11    0     0    14     0     0
15    0     0    11    0     0    14     0     0
15    0     0    11    0     0    16     0     0
12    0     0    11    0     0    16     0     0
13  -18    17    17  -19    13    14     0     0
18    0     0    17  -19     0    14     0     0
18    0     0    14    0     0    19     0     0
15    0     0    14    0     0    19     0     0
19    0     0    15    0     0    20     0     0
16    0     0    15    0     0    20     0     0
21  -20    17    17  -19    21    22     0     0
18    0     0    17  -19     0    22     0     0
22    0     0    18    0     0    23     0     0
19    0     0    23    0     0    18     0     0
23    0     0    19    0     0    24     0     0
20    0     0    19    0     0    24     0     0
25  -21    21    21  -20    25    26     0     0
22    0     0    21  -20     0    26     0     0
26    0     0    22    0     0    27     0     0
23    0     0    22    0     0    27     0     0
27    0     0    23    0     0    28     0     0
24    0     0    23    0     0    28     0     0
29  -22    25    25  -21    29    30     0     0
26    0     0    25  -21     0    30     0     0
30    0     0    26    0     0    31     0     0
27    0     0    26    0     0    31     0     0
31    0     0    27    0     0    32     0     0
28    0     0    27    0     0    32     0     0
33  -23    29    29  -22    33    34     0     0
30    0     0    29  -22     0    34     0     0
```

```
            UD(K)=0.DO
            DO 670 L=1,NU
670       UD(K)=UD(K)+A(K,L)*UDO(L)
700     CONTINUE
800     DO 810 I=1,NU
810     UO(I)=U(I)
        RETURN
        END
//GO.SYSIN DD *
 1000.0     4.921    22.326     5.715      23.0      16.0      34.0 10004112.0
  500.0   500.0 .100E+001 .100E+001 .500E+001    55    80    44    28    11
    0.0000     2.0000 .350E+001 .392E+000  500.0000
    0.0000     1.5000 .350E+001 .392E+000  500.0000
    0.0000     1.0000 .350E+001 .392E+000  500.0000
    0.0000     0.5000 .350E+001 .392E+000  500.0000
    0.5000     2.0000 .350E+001 .392E+000  500.0000
    0.5000     1.5000 .350E+001 .392E+000  500.0000
    0.5000     1.0000 .350E+001 .392E+000  500.0000
    0.5000     0.5000 .350E+001 .392E+000  500.0000
    1.0000     2.0000 .350E+001 .392E+000  500.0000
    1.0000     1.5000 .350E+001 .392E+000  500.0000
    1.0000     1.0000 .350E+001 .392E+000  500.0000
    1.0000     0.5000 .350E+001 .392E+000  500.0000
    1.5000     2.0000 .350E+001 .392E+000  500.0000
    1.5000     1.5000 .350E+001 .392E+000  500.0000
    1.5000     1.0000 .350E+001 .392E+000  500.0000
    1.5000     0.5000 .350E+001 .392E+000  500.0000
    2.0000     2.0000 .350E+001 .392E+000  500.0000
    2.0000     1.5000 .350E+001 .392E+000  500.0000
    2.0000     1.0000 .350E+001 .392E+000  500.0000
    2.0000     0.5000 .350E+001 .392E+000  500.0000
    2.5000     2.0000 .350E+001 .392E+000  500.0000
    2.5000     1.5000 .350E+001 .392E+000  500.0000
    2.5000     1.0000 .350E+001 .392E+000  500.0000
    2.5000     0.5000 .350E+001 .392E+000  500.0000
    3.0000     2.0000 .350E+001 .392E+000  500.0000
    3.0000     1.5000 .350E+001 .392E+000  500.0000
    3.0000     1.0000 .350E+001 .392E+000  500.0000
    3.0000     0.5000 .350E+001 .392E+000  500.0000
    3.5000     2.0000 .350E+001 .392E+000  500.0000
    3.5000     1.5000 .350E+001 .392E+000  500.0000
    3.5000     1.0000 .350E+001 .392E+000  500.0000
    3.5000     0.5000 .350E+001 .392E+000  500.0000
    4.0000     2.0000 .350E+001 .392E+000  500.0000
    4.0000     1.5000 .350E+001 .392E+000  500.0000
    4.0000     1.0000 .350E+001 .392E+000  500.0000
    4.0000     0.5000 .350E+001 .392E+000  500.0000
    4.5000     2.0000 .350E+001 .392E+000  500.0000
    4.5000     1.5000 .350E+001 .392E+000  500.0000
    4.5000     1.0000 .350E+001 .392E+000  500.0000
    4.5000     0.5000 .350E+001 .392E+000  500.0000
    5.0000     2.0000 .350E+001 .392E+000  500.0000
    5.0000     1.5000 .350E+001 .392E+000  500.0000
    5.0000     1.0000 .350E+001 .392E+000  500.0000
    5.0000     0.5000 .350E+001 .392E+000  500.0000
```

```
 .500E+03 .500E+03 .500E+03 .000E+00 .000E+00 .000E+00 .202E+00 .174E+01
 .267E+01 .344E+01 .409E+01 .486E+01 .522E+01 .575E+01 .623E+01 .671E+01
 .360E+01 .000E+00 .000E+00 .000E+00
 1000.0000 0003.4417 0023.0000 0004.9213 0005.7150 0022.3266
 0000.8000 5.080E-03 0015.0000 0000.0000 0016 0034 0000 0004
 0002 0002 0002.5400 0000.0000 0000.0000
 0500.0000 0500.0000 0500.0000 0500.0000 0000.9500 1.000E+04
 0170.0000
 0052.4007 0.800E-05 0007.6500 0075.6400 0038.0000
           0001.0000 0007.6500 0075.6400 0038.0000
           0000.0100 0007.6500 0075.6400 0038.0000
           0000.0100 0007.6500 0075.6400 0038.0000
-   .1000
 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03
 .500E+03 .500E+03 .500E+03 .000E+00 .000E+00 .000E+00 .202E+00 .174E+01
 .267E+01 .344E+01 .409E+01 .486E+01 .522E+01 .575E+01 .623E+01 .671E+01
 .360E+01 .000E+00 .000E+00 .000E+00
 1000.0000 0003.4417 0023.0000 0004.9213 0005.7150 0022.3266
 0000.8000 5.080E-03 0015.0000 0000.0000 0016 0034 0000 0004
 0002 0002 0002.5400 0000.0000 0000.0000
 0500.0000 0500.0000 0500.0000 0500.0000 0000.9500 1.000E+04
 0180.0000
 0078.7007 0.800E-05 0005.3000 0051.2800 0026.0000
           0001.0000 0005.3000 0051.2800 0026.0000
           0000.0100 0005.3000 0051.2800 0026.0000
           0000.0100 0005.3000 0051.2800 0026.0000
-   .1000
 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03
 .500E+03 .500E+03 .500E+03 .000E+00 .000E+00 .000E+00 .202E+00 .174E+01
 .267E+01 .344E+01 .409E+01 .486E+01 .522E+01 .575E+01 .623E+01 .671E+01
 .360E+01 .000E+00 .000E+00 .000E+00
 1000.0000 0003.4417 0023.0000 0004.9213 0005.7150 0022.3266
 0000.8000 5.080E-03 0015.0000 0000.0000 0016 0034 0000 0004
 0002 0002 0002.5400 0000.0000 0000.0000
 0500.0000 0500.0000 0500.0000 0500.0000 0000.9500 1.000E+04
 0190.0000
 0085.6907 0.800E-05 0002.9500 0026.9200 0014.0000
           0001.0000 0002.9500 0026.9200 0014.0000
           0000.0100 0002.9500 0026.9200 0014.0000
           0000.0100 0002.9500 0026.9200 0014.0000
-   .1000
 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03
 .500E+03 .500E+03 .500E+03 .000E+00 .000E+00 .000E+00 .202E+00 .174E+01
 .267E+01 .344E+01 .409E+01 .486E+01 .522E+01 .575E+01 .623E+01 .671E+01
 .360E+01 .000E+00 .000E+00 .000E+00
 1000.0000 0003.4417 0023.0000 0004.9213 0005.7150 0022.3266
 0000.8000 5.080E-03 0015.0000 0000.0000 0016 0034 0000 0004
 0002 0002 0002.5400 0000.0000 0000.0000
 0500.0000 0500.0000 0500.0000 0500.0000 0000.9500 1.000E+04
 0200.0000
 0073.8000 0.800E-05 0000.6000 0002.5600 0002.0000
           0001.0000 0000.6000 0002.5600 0002.0000
           0000.0100 0000.6000 0002.5600 0002.0000
           0000.0100 0000.6000 0002.5600 0002.0000
-   .1000
```

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 31    0    0   30    0    0   35    0    0
 31    0    0   35    0    0   32    0    0
 36    0    0   32    0    0   35    0    0
 37  -24   33   33  -23   37   38    0    0
 34    0    0   33  -23    0   38    0    0
 34    0    0   35    0    0   38    0    0
 39    0    0   35    0    0   38    0    0
 39    0    0   35    0    0   40    0    0
 36    0    0   35    0    0   40    0    0
 41  -25   79   42  -12   41   37  -24   41
 38    0    0   42    0    0   37    0    0
 42  -12   43   43  -13   42   38    0    0
 39    0    0   43  -13    0   38    0    0
 43  -13   44   44  -14   43   39    0    0
 40    0    0   39    0    0   44  -14    0
  4  -28   45   45    1    0    8    0    0
 46    2    0   45    1    0    8    0    0
 46    2    0   47    3    0    8    0    0
 12    0    0    8    0    0   47    3    0
 47    3    0   12    0    0   48    4    0
 16    0    0   12    0    0   48    4    0
 20    0    0   16    0    0   49    5    0
 48    4    0   49    5    0   16    0    0
 24    0    0   20    0    0   50    6    0
 49    5    0   20    0    0   50    6    0
 28    0    0   24    0    0   51    7    0
 50    6    0   24    0    0   51    7    0
 28    0    0   32    0    0   51    7    0
 52    8    0   51    7    0   32    0    0
 36    0    0   53    9    0   32    0    0
 52    8    0   53    9    0   32    0    0
 40    0    0   54   10    0   36    0    0
 53    9    0   54   10    0   36    0    0
 44  -14   55   40    0    0   55   11    0
 54   10    0   55   11    0   40    0    0
  1
 101.325  300.000   50.0    151.000    1.000  50 92484
  1
1715.61 1805.19 1901.64 1991.21 2094.56 2273.70 2389.94 2501.07 2631.98 2859.35
3026.46 3217.63 3410.55 3610.36 3844.62 3851.00 4092.66 4347.59 4878.12 5139.94
5408.65 5684.25 5959.85 6235.45 6511.05 6779.76 7027.80 7068.95 7510.10 7716.00
7928.10 8095.75 8233.55 8302.45 8350.68 8371.35 8378.24 8385.13 8392.02 8398.91
8398.91 8392.02 8378.24 8343.79 8260.00 8164.65 8026.85 7854.60 7579.00 7234.00
1000.0000 0003.4417 0023.0000 0004.9213 0005.7150 0022.3266
0000.8000 5.080E-03 0015.0000 0000.0000 0016 0034 0000 0004
0002 0002 0002.5400 0000.0000 0000.0000
0500.0000 0500.0000 0500.0000 0500.0000 0000.9500 1.000E+04
0160.0000
0029.1007 0.800E-05 0010.0000 0100.0000 0050.0000
          0001.0000 0010.0000 0100.0000 0050.0000
          0000.0100 0010.0000 0100.0000 0050.0000
          0000.0100 0010.0000 0100.0000 0050.0000
-   .1000
.500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03
```

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.500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03 .500E+03
.500E+03 .500E+03 .500E+03 .000E+00 .000E+00 .000E+00 .202E+00 .174E+01
.267E+01 .344E+01 .409E+01 .486E+01 .522E+01 .575E+01 .623E+01 .671E+01
.360E+01 .000E+00 .000E+00 .000E+00

/*
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END

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